Welsh Office

A Selection of Technical Reports Submitted to The Aberfan Tribunal

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A Selection of Technical Reports submitted to the Aberfan Tribunal

Foreword

In our Report* published last year we said that as soon as we were constituted as a Tribunal we arranged for a series of scientific investigations to be started under the general direction of Professor A.W. Bishop, London University. The National Coal Board brought in expert members of its own staff and also independent experts and the Aberfan Parents' and Residents' Association likewise engaged independent expert advisers. In addition certain other investigations were put in hand on behalf of some of the parties who appeared before the Tribunal. In view of their scientific interest, we thought it right to arrange for the separate publication of seven of the reports submitted by these experts to the Tribunal, and they are reproduced here with exactly the same text as was originally submitted. Most of the original drawings were unsuitable for reproduction within the size of this publication and many have been re-drawn. In some cases there was sufficient similarity between the drawings used by different experts to make it possible to use one drawing here without detracting from the information given in the original report.

Certain of the written reports submitted to the Tribunal were required simply as formal evidence and these have not been reproduced in this publication.

The task of preparing this volume for publication has been performed by Mr A.D.M. Penman with assistance from the authors of the reports and others. We acknowledge our debt to him and to all who helped him.

EDMUND DAVIES
HAROLD HARDING
VERNON LAWRENCE

R. LLOYD THOMAS, *Secretary*
November 1968

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*H.L. 316
H.C. 553

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Geotechnical Investigation into the Causes and Circumstances of the Disaster of 21st October, 1966

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1 Introduction

In preparing this Report we have attempted to give a concise summary of those aspects of our investigation which appear to be directly relevant to the four questions posed by the Chairman at the opening session of the Tribunal:

(1) What exactly happened?
(2) Why did it happen?
(3) Need it have happened?
(4) What lessons are to be learnt from what happened at Aberfan?

Details of tests are given in appendices, together with information which appears at this stage to be of marginal relevance to the four questions, but which may be of value to future studies in this field. In this latter connection we would draw attention to the present lack of information on the engineering properties and behaviour of tip materials and on the seasonal variations in water pressure within tips and the strata on which they are founded. It will be one of our recommendations that some of the observations and investigations begun during this present Inquiry should be continued, under the sponsorship of the National Coal Board, the Science Research Council or the National Environmental Research Council, by the Institute of Geological Sciences, the Building Research Station and appropriate University Departments of Civil Engineering and Mining Engineering.

A rigorous scientific investigation involving precise calculations of the factor of safety of the structure has been particularly difficult in this case. The structure with which the Inquiry is concerned, though comparable in magnitude with our major road or reservoir embankments (the height from toe to crest being about 200 ft) is a colliery rubbish tip, and the stages of its construction and its shape immediately prior to the slip of October 1966 are not well documented. The internal water pressures in the foundation and the tip were not measured and have since been substantially modified. Most of the relevant material from the tip has moved many hundreds of yards down the mountainside.

Our conclusions therefore depend not only on the measurement of the properties of the foundation strata and the tip material, but on a careful examination of the behaviour of the tip in the years preceding the ultimate collapse. In this examination we have enjoyed the co-operation of the Ordnance Survey, the Royal Air Force, Hunting Surveys Ltd, the Department of Photogrammetry and Surveying of University College London, and the Meteorological Office. The programme of boreholes has been planned jointly with Dr A.W. Woodland, of the Institute of Geological Sciences, and co-ordinated with work initiated by the National Coal Board. Borehole logs have been agreed by the geologists of the I.G.S. and the N.C.B. Some 80 boreholes have been completed and are shown on Fig. 1.1 (folded drawings are contained in the wallet).

The National Coal Board have co-operated most willingly in the provision of offices, heavy plant to facilitate the site investigation, and where necessary photographic and surveying services, often at very short notice. Some difficulties have arisen in carrying out our investigation due to safety requirements and due to the problems involved in handling heavy plant and carrying out large-scale earth-moving operations under the prevailing weather conditions. Very significant data about the nature of the slip under the southern section of the tip, only began to be available to us on 8th February 1967 and the area immediately uphill of the spring revealed by the October 1966 slip has not been cleared at the date of writing this Report.

In examining the data on which this Report is based it has become apparent to us that all the events contributing to the disaster cannot be associated with a single cause. Several factors were involved, which separately could have caused a slip, though not necessarily a disastrous one. Our conclusions depend on the general agreement of data from a number of sources, and are not dependent on the precise measurement of particular properties or dimensions.

Evidence given during the course of this Inquiry indicates that it is necessary to clarify the distinction between an unsafe and a safe structure. The fact that a structure is standing at the time of inspection is, by itself, no indication that it will not collapse the following day. A discussion of the engineering concept of 'factor of safety' is outside the scope of this Report, but is presented most lucidly in Chapters 11, 12 and 13 of a short book by Sir Alfred Pugsley entitled *The Safety of Structures* (1966).

2 Some earlier slips in South Wales and their relevance

It is relevant to the four questions posed by the Chairman of the Tribunal to examine the background of earlier slips in the Welsh valleys against which the present disaster is to be seen. An exhaustive survey has not been attempted, but the following information is considered to be useful.

(I) *A paper on 'Landslides in South Wales Valleys' by Professor George Knox, FGS, MIME, read and discussed in 1927*

This paper was read and discussed in Cardiff on 29th March 1927, with further remarks and discussion on 28th April 1927. This is published in full in the *Proceedings of the South Wales Institute of Engineers*, Vol. 43, pp. 161–247 and 257–290. A critical summary is given in Appendix 1.

This paper is of importance because of the great interest which it aroused at the time in landslides, including slides involving colliery refuse. Though Knox's understanding of the physical mechanism and applied mechanics of the slide is now considered inadequate, he correctly emphasised the over-riding importance of water in causing landslides. He also recognised that in the area of South Wales under discussion most of the water concerned in a landslide is derived from percolation from the joints of the Pennant sandstone rather than from direct rainfall on the slide area.

Knox recognised that the most generally effective measure for remedying landslides was adequate drainage of the seat of the slide. In the discussion reference was made to preparatory drainage of sites selected for tipping. The hope was expressed that 'mining engineers would make a more careful investigation of so-called suitable ground for colliery tips'.

(II) *The Abercynon slide on 5th December, 1939*

This slide is described in the following documents:

(a) An unsigned Powell Duffryn report dated December 1939. This is accompanied by two survey drawings dated 8th January 1940.
(b) A report prepared by Mr W. Brynmor Davies entitled 'Rubbish Tip Slide, Cilfynydd Common, on 5th December 1939'. This includes photographs of the slide and was presented in February 1940.
(c) Report in the *South Wales Echo* on 5th December 1939.
(d) Report in the *Western Mail* on 6th December 1939. This report is included as Appendix 2.
(e) A text-book for mining engineers by Professor J. Sinclair entitled *Ground Movement and Control at Collieries* and published in 1963.

The reports are in general agreement in their description of the slide. The slide occurred at about 1.40 p.m. on 5th December about one week after a period of unusually heavy rainfall (details of which are given in evidence from the Meteorological Office). The slide travelled down the mountainside for about 1430 ft, 'at a terrific speed' according to the Press accounts, blocked the roadway for 585 ft with rubbish to a depth of 8 ft, breached the canal and blocked the River Taff with rubbish to a depth of 15 ft.

This slip, which is the nearest parallel in its speed and destructive effect to that at Aberfan and could have resulted in a similar disaster had inhabited property lain in its path, was visited briefly by the senior author of this Report in 1940 and left a lasting impression.

The slip is relevant to the present investigation in several respects:

(i) It took the form of a destructive flow slide although accompanied by no significant outflow of water. A comparison of the sections of the slides at Abercynon and at Aberfan in 1966 (Fig. 1.2 in wallet) shows that over much of its path the former slide had a flatter gradient.

(ii) The material did not include tailings of the type tipped at Aberfan from February 1962.

(iii) It was an active tip, placing of material at the relevant section having taken place shortly before the failure. The photographs accompanying the report by Mr Brynmor Davies (for example, Fig. 1.3) suggest that the original cross-section indicated on his survey is nominal and is dissimilar to the actual profile of the remaining sections of the tip immediately adjacent to it.

(iv) An 'ominous move' of the tip on the day before the final slip is referred to in the Press reports. The survey plan included in the Powell Duffryn reports suggests that the toe of the tip had bulged at this section at an earlier date.

(v) The original version of the Powell Duffryn Report entitled 'The sliding of colliery rubbish tips' was dated December 1939 and, it may be inferred, was a consequence of this event.

The various reports are not in agreement as to the initial cause of the slip, and differ from the explanation given to the senior author in 1940. In the absence of a detailed investigation we can only suggest that several of the factors found to have been operative at Tip 7 at Aberfan would be of significance in this case also:

(a) The Geological Report by Dr A.W. Woodland indicates that the tip lay across the probable spring line of water emerging from the Daren-ddu sandstones and over a seepage point of water from the Cefn-Glas sandstone.

(b) The material was loosely dumped, the outer part by over-tipping. For the material to be in a loose state is a pre-requisite of flow slides.

(c) Some prior movement occurred.

(d) The foundation consisted of Head and Boulder Clay, which can have a lower angle of internal friction than tip rubbish, sloping steeply towards the valley. Excess pore pressure below the boulder clay was likely in periods of heavy rainfall.

(III) *The slide at Tip 4 at Aberfan on 21st November 1944*

The slide is described in the evidence before the Tribunal. It is also described in the following documents:

(a) Photographic Interpretation Report of the Joint Air Reconnaissance Intelligence Centre (U.K.) (J.A.R.I.C.), and of Fairey Surveys Ltd. Photography of 3rd August 1945 (their Fig. 1 *et seq.* see Item 8).

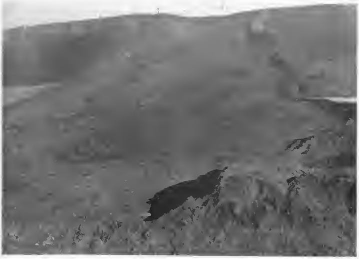
(b) Interpretation and Analysis of Photography covering the Aberfan Area by Fairey Surveys Ltd (their Fig. 1 *et seq.*).

(c) Ordnance Survey Map dated 1957.

A major rotational slip took place accompanied by a flow slide on a rather narrow front reaching to within 550 ft of the disused canal above the school.

The slip is relevant to the present investigation in several respects:

(i) It took the form of a potentially destructive flow slide, although accompanied by no significant outflow of water. The gradient on which it flowed is much the same as at Tip 7 at Aberfan in 1966. The developed sections are compared in Fig. 1.2.



1.3 Flowslide at Abercynon, December 1939

(ii) The material did not include tailings of the type tipped at Aberfan from February 1962.

(iii) It was an active tip, placing of material having continued until the final failure.

(iv) Some sliding of the tip had occurred before the final failure.

This is supported by statements made in evidence before the Tribunal. It is also supported by our interpretation of the spurs extending from the tip to the south-west on either side of the slide and particularly on the southern side. These appear on J.A.R.I.C. Fig. 1, and rather more clearly on their Fig. 4 (photography of 12th October 1951). The interpretation by Fairey Surveys Ltd supports this view and on their Fig. 1, note 108, indicates the estimated outline of the southern base of Tip 4 prior to the slide. Similar but smaller spurs may be seen on the Powell Duffryn plan of the Abercynon slip. A detailed examination of this slip has not been carried out, but attention is drawn to several features:

(a) The Geological Report by Dr A.W. Woodland indicates that the tip lay across the outcrop of a thin mudstone, possibly at the horizon of the Brithdir Rider. The 'rise' of stream on the Ordnance Map surveyed in 1898 approximates to this position.

(b) The material was loosely dumped, which is a prerequisite of a flow slide.

(c) Some prior movement occurred, probably of large magnitude. Detailed evidence in quantitative terms is difficult to obtain on this point due to the absence of earlier low-level aerial photography.

(d) The preceding rainfall was heavy but not unusual and corresponded closely to that at Aberfan prior to the October 1966 slip. Details are given in the evidence to the Tribunal from the Meteorological Office.

(IV) *The slide at Tip 7 at Aberfan, 1963*

Further reference to this slip will be made in section 7 (p. 21). Evidence before the Tribunal suggests that a significant rotational slide accompanied by a small[1] flow slide occurred in the second half of October or the first half of November 1963.

This is supported by evidence given by the tipping gang, by the interpretation of aerial photography (for example, J.A.R.I.C. and Fairey Surveys Ltd, Fig. 8, notes 55 and 56), and by the evaluation of quantities (Appendix 6). It is also consistent with the nature of the slip surface discussed in section 8 (p. 30) and with the lack of forward progress of the crest of the tip indicated by the cross sections (Fig. 1.4a).

(V) *The failure of the tip at Tymawr in 1965*

From the information available to us it appears that this breaching of the tip was different in character from the slides mentioned in sections 2(II), 2(III), 2(IV) and from the final slip at Aberfan in October 1966.

It is of interest to the present Inquiry in two respects:

(a) It occasioned the circulation of the Powell memorandum dated 12th April 1965 requesting the inspection of tips.

(b) It illustrates that damaging failures can occur under conditions quite different from those at Aberfan. Another example is the collapse of a slurry pond on 24th March 1966 at Williamthorpe Old Dirt Tip, which covered an adjacent road to a maximum depth of 10 ft and closed it for 10 days.

3 Geology of the site in the immediate vicinity of the tip and geotechnical properties of the natural strata

Aberfan is situated in the valley of the River Taff on the northern limb of the broad structural basin of the South Wales coalfield. In this vicinity the Taff runs in a southerly direction and is incised over 1000 ft

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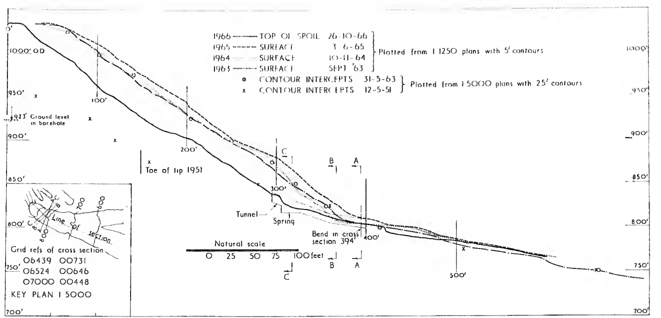
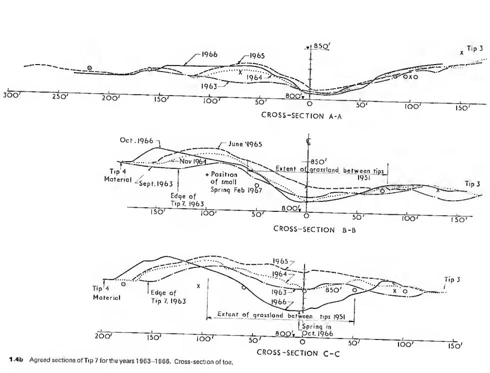
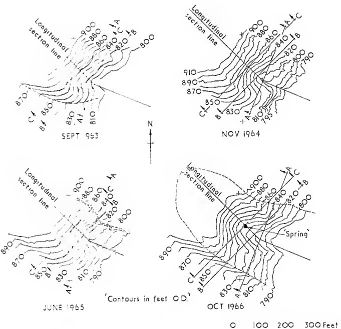
[1] This is a relative term. While small compared with the October 1966 slide, its volume probably greatly exceeded that of the Tymawr failure in 1965. (See Appendix 6.)



1.4a Agreed sections of Tip 7 for the years 1963–1966. Section through crest.



1.4b Agreed sections of Tip 7 for the years 1963–1966. Cross-section of toe.



1.4c Agreed sections of Tip 7 for the years 1963–1966 Contours of toe

below the surface of the rolling plateau of Pennant Measures which forms the interfluves. The complex of tips of colliery waste above Aberfan rests on the western slopes of the Taff valley. These slopes have an average inclination of approximately 12° (1 in 4·7) and extend from about –450 ft to –1450 ft O.D.

The solid geology of the tipping area has been described by Dr A.W. Woodland in the Geological Report of the Aberfan Tip Disaster (Item 4). It is illustrated, in relation to the various tips, on the agreed Aberfan Geological Plan (H9) and its accompanying Horizontal Sections (H 10A and H 10B) (see notes on p. 103). The above documents also give a general indication of the character of the local superficial deposits.

The whole of the hillside in the vicinity of the Aberfan tip complex is mantled by a layer of drift deposits. The greatest proven thickness of these is 77 ft in borehole L11. The average thickness of drift beneath the tips is probably rather less than half this, and locally in the vicinity of the 'spring' the thickness is much less. The extent and nature of this drift mantle is relevant to the current investigation in two ways. Firstly, as in general much of the drift is of lower permeability than the underlying jointed rock masses, it exerts a major influence on the magnitude and distribution of the ground-water pressures acting within the mountain. In the second place, as the drift mantle underlies all the tips, its strength as a foundation material is of importance.

The stoniness of much of the Aberfan drift has rendered it difficult to sample effectively using soft ground techniques. On the other hand the content of uncemented material is usually such that poor cores are obtained by rotary drilling methods. These factors, in conjunction with the inherent variability of the drift mantle, have considerably hampered its investigation.

Available evidence on the geology in the immediate vicinity of Tip 7 is summarised in Figs. 1.5 and 1.6. These show respectively sections downslope and cross-slope through the position of the spring which was exposed beneath Tip 7 after the disaster of October 1966. The subsurface detail is based on the results of rotary borings, shallow excavations, trial pits and soft ground borings. The surface profiles are taken from appropriate photogrammetric and tacheometric surveys. The lines of these two sections are shown on Fig. 1.7.

Tip 7 is sited over the outcrop of the Brithdir Beds, which consist locally almost entirely of Pennant sandstones. At the base of these is the Brithdir coal, which outcrops beneath the drift some 50 to 100 yards downslope from the toe of the tip. This coal seam is underlain by about 70 ft of predominantly mudstone strata which rest on further beds of sandstone. In this vicinity the solid strata dip at about 5° (1 in 12) to the south-south-east. Their component of dip towards the valley is about 4° (1 in 15).

The layer of drift lying between the base of the tips and undoubted rock-head comprises broadly three components:

(i) An uppermost, ubiquitous mantle of Head. This is made up of solifluction, scree, hill-wash and superficial creep deposits which have presumably accumulated during the Late- and Post-Glacial period. The character of these deposits reflects their derivation from the slopes directly above their present location. On the slopes immediately below Tip 7, the Head consists typically of a thin spread of buff, somewhat silty, fine sand (presumably hill-wash) overlying some feet of yellow sandy clay which contains stones that are predominantly of Pennant.

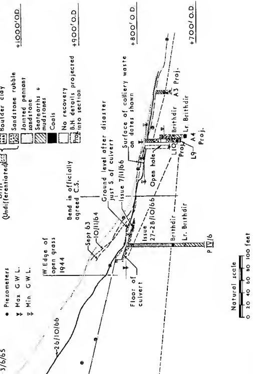
(ii) In certain areas of the lower slopes of the hillside the Head is underlain by a layer of Boulder Clay, presumably of Weichselian age. Although somewhat variable, this till seems to consist typically of a matrix of firm to stiff, grey-brown silty clay containing rock debris up to boulder size. Its suite of erratics is consistent with deposition by a glacier moving down the Taff valley from a source in the neighbourhood of the Brecon Beacons.

(iii) In an area immediately downslope from Tip 7 the base of the drift is occupied by a layer of Pennant debris. The high, rather random dips observed in particularly the upper part of this layer suggest that it has been subjected to some degree of movement. The lower part of the layer appears to consist of weathered rock-head, virtually *in situ*. Both types of debris contain interstitial sandy clay. They will be referred to jointly as Sandstone Rubble.

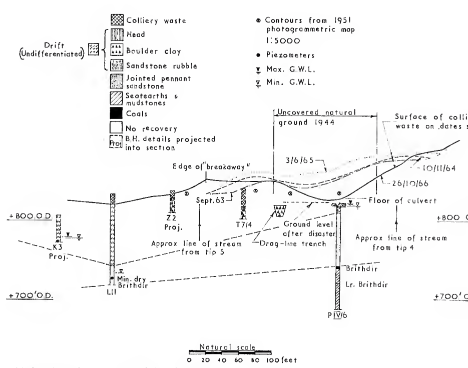
The approximate extent and thickness of these three components of the drift in the immediate vicinity of Tip 7 are indicated on the sections shown on Figs. 1.5 and 1.6. While the boundaries shown must generally be regarded as tentative, the broad pattern is reasonably well established. The uppermost layer of Head is everywhere present and appears to vary in thickness from about 4 to 10 ft. The underlying tongue of Boulder Clay is confined to the shallow embayment in the valley side to the south of the lower part of the tip complex, as shown by the Aberfan Geological Plan, Fig. 4.2 (in wallet). The northern edge of this tongue extends under the southern part of the top of Tip 7, feathering out on a generally east–west line in the neighbourhood of the spring by borehole PIV/6. The available detail of the location of the feather edge is shown on Figs. 1.5 and 1.6.

The upper surface of the layer of Sandstone Rubble is exposed in the uppermost 70 ft of the floor of the arched culvert.

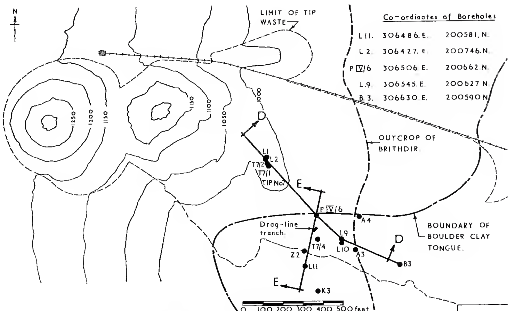
Information on the geotechnical properties of the drift deposits has



1.5 Down-slope section D–D through 'spring' at borehole PIV/6.



1.6 Cross-slope section E–E through 'spring' at borehole PIV/6



Co-ordinates of Boreholes

L 11.	306486. E.	200581. N.
L 2.	306427. E.	200746. N.
P IV/6	306506 E.	200662 N.
L. 9.	306545. E.	200627 N.
B 3.	306630 E.	200590 N.

1.7 Part of agreed geological plan showing locations of sections D–D and E–E.

been obtained chiefly from laboratory tests on about 30 samples. These have been taken from between depths of about 1 and 20 ft in boreholes and trial excavations located in the vicinity of the seat of failure below Tip 7. The majority of the samples were taken by open-drive samples of 4-in. nominal diameter (U4 samples). The remaining samples were taken either by driving a $1\frac{1}{2}$-in. diameter metal tube (U$1\frac{1}{2}$ samples) or by cutting a block of soil by hand. Locations of the samples tested and details of the results obtained are given in Appendix 3.

The impractibility of defining accurately the boundary between the Head and the Boulder Clay usually prevents firm allocation of the test results to one deposit or the other. A summary of the properties determined for the upper drifts[1] in the area below the toe of Tip 7 is given in Table 1. These properties have been measured on the finer matrix of the drifts,[2] either from $\frac{1}{2}$ in. down or from sieve 7 size (*c.* $\frac{1}{10}$ in.) down. They are typical of a lean, inorganic, over-consolidated clay. Drained triaxial tests show that in terms of effective stresses the material has zero cohesion intercept and an angle of internal friction which ranges from 29° to 40°. The magnitude of the latter parameter tends to decrease as the clay content of the soil increases. The residual shear strength has been measured on one sample of the drift and is not significantly lower than the peak shear strength. There is some indication from the laboratory tests (Appendix 3) that the bulk density of the matrix of the Head is distinctly lower than that of the Boulder Clay; of the order of 125 lb/ft^3 as compared with 135 lb/ft^3.

Table 1
Geotechnical properties of the upper drifts in the area
of the toe of Tip 7

	Description	Unit	Magnitude		
			Min.	Max.	Average
	Bulk density, γ	lb/ft^3	118	140	130
	Natural water content, w	%	10	36	16
	Liquid limit, w_L	%	14	42	24
	Plastic limit, w_P	%	13	29	16
	Plasticity index, I_P	%	2	13	8
	Clay content ($<2\mu$)	%	3	25	13
	Activity	—	—	—	0·6
In terms of effective stresses	Cohesion intercept, c′	lb/ft^2	0	0	0
	Angle of internal friction, $\varnothing'$	degrees	29	40	36
	Permeability (from falling head tests)	cm/sec	4×10^{-6}	5×10^{-5}	3×10^{-5}
	Specific gravity of particles	—	2·55	2·60	2·58

The permeability values given in Table 1 have been obtained from falling head tests on piezometers installed in the drift, and must be regarded only as a rough indication of the actual permeabilities. The locations and results of the various falling head tests made are detailed in Appendix 3. One laboratory permeability determination has been made on a 4-in. long, 4-in. diameter sample of Head taken from immediately below the exposed slip surface in Tip 7 at the location 306485E, 200635N (*c.* +837 ft O.D.). The test was carried out in an oedometer under a vertical load of about 60 lb/in.^{2} and at a constant temperature of 70°F. The measured permeability was $4{\cdot}1\times10^{-8}$ cm/sec.

Little is known of the mechanical properties of the layer of Sandstone Rubble. It is clearly stronger than the overlying drifts and neither it nor the underlying solid rocks was involved in the shear failures beneath

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[1] That is, the undifferentiated Head and Boulder Clay. The Sandstone Rubble layer is not included in the table.

[2] Boulders several feet across have been found in the Boulder Clay.

Tip 7. A sample of the interstitial clayey material, taken from the artificially cut face a few feet above the borehole PIV/6, had a water content of 13% and liquid and plastic limits of 16 and 15% respectively. No direct measurements of the permeability of this layer have been made but general observation of the material in the floor of the culvert suggests that its permeability is relatively high. Some support for this view is provided by the readings of ground-water levels at boreholes PIV/6 and L9.

4 Ground-water conditions

An analysis in general terms of the ground-water conditions existing in the mountain beneath the tip complex is contained in Dr A.W. Woodland's Geological Report and the Appendix by Mr D.A. Gray (Item 4).

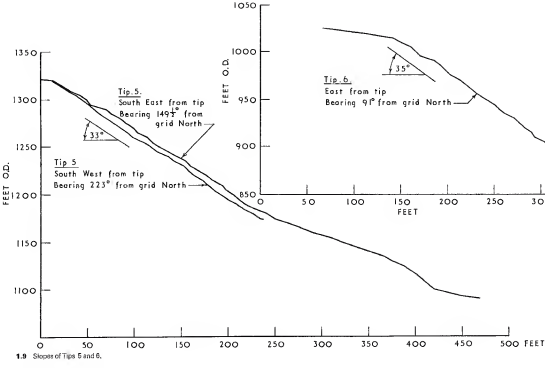
The ground-water conditions in the Brithdir Sandstone, which underlies that part of the hillside upon which Tip 7 is sited, have been explored by means of a number of piezometers. These are installed in a line of boreholes which follows approximately the dip direction of the solid strata and passes through the position of the spring at borehole PIV/6. This line coincides closely with the centreline of Tip 7.

A section along this line of piezometers is given in Fig. 1.8 (in wallet), on which the highest and lowest water levels so far recorded are shown. In general, observations are available from February 1967. In most cases the lowest piezometric levels were observed on or about 16th February and the highest on or about 1st March. Comparison of these observations with the rainfall data confirms that changes in ground-water level in the Brithdir Sandstone lag about two days behind changes in rainfall.

The section of Fig. 1.8 shows that at borehole R6 on the upper slopes of the hillside the ground-water levels in the Brithdir Sandstone fluctuate between extremes of about 75 and 145 ft below ground level. From these the free ground-water surface falls at an average slope of about 1 in 12 to meet the ground surface in the vicinity of the 'spring' at borehole PIV/6. Most of the piezometers on the hillside below the spring are installed either in the layer of Sandstone Rubble, which appears to be in direct hydraulic communication with the Brithdir Sandstone, or in the sandstones below the Brithdir seams. These piezometers generally indicate artesian pressures, the less permeable upper drift mantle providing a confining layer.

The conditions immediately downslope from the 'spring' are shown in more detail on the section of Fig. 1.5. Of particular interest is piezometer L9 which is installed at the base of the Sandstone Rubble and indicates an artesian ground-water pressure, with respect to the interface between the tip rubbish and the drift, which ranges from about 12 to 20 ft (−785·9 to −793·6 ft O.D.). Prior to the discharge of water associated with the disaster of October 1966 the ground-water pressures at this point are likely to have been greater than any pressures measured subsequently. The maximum piezometric level observed since the disaster, of −793·6 ft O.D., may be taken as a reasonable lower bound for the piezometric level immediately before the disaster at the position now occupied by piezometer L9.

An upper bound for this pressure may be arrived at as indicated below. The 1951 air survey indicates that the natural ground level at L9 before any tipping took place on the hillside was approximately 10 ft above the present broken surface of the drift (Fig. 1.5). As this drift-covered hillside had remained stable through the years before tipping started, it can be concluded that the ground-water pressures in the underlying Sandstone Rubble had never, in all this time, reached a high enough value to cause the drift mantle in this vicinity to slide off. The piezometric level required to produce such a failure could be taken as the upper bound for the pressure immediately before the disaster, were it not for the possibility that the placing of the tips on the hillside has altered the hydrological conditions in the mountain, for instance by



1.9 Slopes of Tips 5 and 6.

restricting previous points of ground-water discharge. The calculation is carried out, therefore, for the latest pre-disaster conditions for which photogrammetric data is available, i.e. 3rd June 1965. This indicates that the maximum piezometric level in the Sandstone Rubble at the location of L9 that could be sustained by the overlying mantle of drift and tip rubbish existing at that date is about +796 ft O.D. The latter figure would of course require to be increased if the profile of the tip immediately before the disaster was higher local to L9 than that surveyed in June 1965.

Similar calculations at the position of the 'spring' indicate the lower and upper bounds of the pre-disaster piezometric level at that point to be about 822 and 836 ft O.D. This latter figure represents a pore-water pressure equal to only about 20% of the weight of overburden, mostly tip rubbish, above this point on 3rd June 1965. This value forms a useful comparison with the values of r_u considered in the stability analyses of Section 8 and Appendix 4.

5 Properties of tip material

Tip 7 is formed of colliery rubbish of which shale, probably derived chiefly from the Lower Coal Measures, is the predominant and most significant component. The tip contains some coal and also general rubbish including some boiler ash, pit props, steel cables, pieces of reinforced concrete, etc. In spite of these hazards, the taking of samples by soft ground techniques has proved surprisingly successful, though some disturbance and density change in the 4-in. diameter samples must be accepted.

In certain zones tailings are encountered almost unmixed with other rubbish and their properties are treated separately.

Details of the mechanical properties of the materials tested are given in Appendix 3, and only the principal features are summarised here.

(a) *Density*

This is expressed as either the bulk density, i.e. the total weight of solid material and water (in lb) per cubic foot of volume, or dry density, i.e. the weight of solid material less the water (in lb) per cubic foot of volume. The latter value is more relevant in comparing the relative looseness or denseness of material, in which the degree of saturation may vary.

Considerable variations in density were encountered in the boreholes. *In situ* values of density by the sand replacement method gave an average value of bulk density of about 110 lb/ft^3 and of dry density 100 lb ft^3.

The Proctor (or B.S.) Optimum Dry density for Tip 7 material was 121 lb ft^3. This is the density produced by normal field compaction equipment. It is relevant to note that a minimum of 95% of this value is usually specified for embankment work and this gives 115 lb/ft^3 in this case. This illustrates the relative looseness of the tip material.

The average of two *in situ* density tests in an undisturbed area of the slipped material not far from the canal (coords 20064mN-30691mE)[1] gave a dry density of 111 lb/ft^3. This is consistent with the view that the flow was associated with a collapse of the granular structure which became denser after shear.

During the investigation a shallow 'mud-run' occurred on Tip 7 following heavy rain. Water content and specific gravity measurements on the moving material enabled its dry density to be determined (on the assumption of full saturation). A series of eight tests gave values ranging from 97 lb/ft^3 to 106 lb/ft^3 under virtually zero idential stress. The dry density at which saturated material will flow under higher stresses is substantially greater (on the basis of published data). It must be inferred therefore that the tip material was placed at a density at which shear displacements could lead to flow slides in saturated or even partly saturated material.

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[1] [illegible] Survey, November 1966 (in wallet)

The looseness of the tip is also confirmed by the low values given by the Standard Penetration Test. Values in the upper part of the tip lay in the range 3 to 36 (see Appendix 3). Loose material is generally considered as lying below a value of 10.

It must be noted that these values of *in situ* density were measured in what remained of the tip. The front portion which slipped may well have been of even lower density.

A sample of fine material, apparently tailings, located near the crest of Tip 7 was found to have an initial water content of 18·2% and a liquid limit of 26·5%. Its constituent particles have an average specific gravity of 1·92. In the semi-fluid state (i.e. at its liquid limit), therefore, its bulk density would be 100 lb/ft^3, dry density 79·3 lb/ft^3, and as sampled (if full saturation is assumed) 105 lb/ft^3 (dry density 88·9 lb/ft^3).

(b) *Strength*

This is expressed as the angle of internal friction, $\varnothing'$, measured in terms of effective stress. This angle varies somewhat with pressure and where this variation is of importance, attention will be drawn to the stress range. Details of the tests are given in Appendix 3.

The samples taken from the boreholes through the crest of Tip 7 gave average values $\varnothing'$ of 39½° in drained tests and of 41½° in undrained tests after allowing for excess pore water pressure. These tests are of only a few hours duration and make no allowance for long-term effects. The comparison given below with the shale fill used in two important embankment dams shows that the Aberfan material has a higher angle of internal friction than that found satisfactory in major water-retaining structures. The latter were designed as structures with due regard to slope angle and drainage.

	$\varnothing'$	*In situ* dry density lb/ft^3	Height (ft)	Average downstream slope
Burnhope Dam (1936)	35°	107	131	19·4°
Balderhead Dam (1965)	34·5°	119	157	19·7°
Aberfan Tip No. 7	39·5°	99	[1]220	[1]36·0°

[1] June 196S

The fact that the older tips at this site have remained stable for considerable heights at slopes of 33° to 35° (Fig. 1.8) indicates that long-term effects may be limited in magnitude or delayed in operation.

The tailings, under fully drained conditions, show a measured value of angle of internal friction, $\varnothing'$, in the range 31°–33°. The difference in their behaviour is due principally to their low permeability and inability to drain freely.

A most significant feature of the strength characteristics of the tip rubbish is the large reduction in angle of internal friction which occurs on surfaces on which large shear displacements have occurred. Evidence of this phenomenon only became available when the slip surface south of the 'spring' was exposed on 8th February 1967 and a detailed study of its cause is still in progress. However, the following facts can be reported.

The lowest values of the residual angle of internal friction, $\varnothing_r'$, on the slip surface were 18½° on a disturbed sample and 17½° on a prepared sample of the smear of fine material immediately adjacent to the slip surface, which was polished and striated (for example, Fig. 10). When the excavation exposing this area was made, the removal of toe support caused a renewal of movements in the remaining tip material above the old slip surface. Stability analyses of this mass gave an average value of [illegible] of 26°, on the assumption of zero excess pore pressure in the tip material (see Section 6).

The origin of the layer of fine material associated with the slip surface is almost certainly connected with the degradation of the shale under shear strains (a similar degradation of the much stronger quartz particles in a sand occurs under high pressures, see Bishop 1966).

Freshly ground shale particles less than 2 microns showed a residual angle of internal friction of 26·7° but had a very low plasticity index (4·4%). This suggests that comminution alone is insufficient to produce the low value of residual shear strength and that it must be accompanied by some process of weathering[1] or hydration of the clay minerals in the shale, on the actual shear surface. The orientation of the clay particles on the slip surface is clearly also of importance since samples of material adjacent to the surface showed appreciably higher strengths if sheared other than along the previously formed surface.

The residual angle of internal friction of the tailings has been found to be almost the same as its peak angle of friction, i.e. about 32°. This suggests that the layer of fines associated with the slip surface does not consist of a layer of tailings as placed, although the possibility of the degradation of the shale content of tailings at very large strains and after weathering cannot be ruled out.

(c) *Permeability*

The permeability of the tip material is variable but on the average the tip is shown by the piezometer readings to be relatively free-draining. A representative sample of tip material gave a permeability of $6{\cdot}6\times10^{-3}$ cm/sec.

A representative sample of the fine material adjacent to the slip surface gave a permeability of $1{\cdot}8\times10^{-9}$ cm/sec. This indicates that large shear strains[2] have an important influence on the permeability of the colliery rubbish.

The permeability of the tailings obtained from consolidation tests was found to be between 2·34 and $1{\cdot}27\times10^{-7}$ cm/sec (average of six tests $1{\cdot}73\times10^{-7}$ cm/sec).

(d) *Sizing analyses*

The grading characteristics of the tip rubbish and the tailings are given in Appendix 3. It is of interest to note that the percentage of fines passing the 200 sieve averaged about 10% for samples taken from the undisturbed tip material. The percentage of fines passing the 200 sieve determined by the same method for samples from the flow slide, however, are as follows:

Mid-way between Tip 7 and the schools	19%
Near the senior school	18%

(e) *Mineralogy of tip material*

The mineralogy of the tip material has been examined at the Building Research Station and the results are given in Appendix 3.

6 Pore pressures in the tip material

Instruments for the measurement of pore-water pressures (piezometers) have been installed in Tips 3, 4 and 7. Details of the observations in these and the other piezometers are given in Appendix 3.

Shallow piezometers of special design were driven, between 12th and 14th November 1966, into the face of Tip 7 left by the failure. These penetrated generally about 20 ft below the surface of the tip. None of them indicated any water pressure. Most of these piezometers were destroyed by shallow slides and 'mud-runs' in early December 1966.

Casagrande type piezometers were installed in boreholes T7/1 and

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[1] Possibly accelerated by the generally acid environment.

[2] Together with the other factors leading to degradation of the shale particles

T7/2 in Tip 7 at approximately the interface between the tip material and the natural ground (Figs. 1.1, 1.5 and 1.8). Typical observations in these piezometers are given in Table 2. They indicate that in general the phreatic surface in Tip 7 is situated close to the surface of the underlying natural ground, although transient rises in pore-water pressure may occur after heavy rain.

Table 2
Observations in piezometers in Tip 7

Date	Rainfall	Ht. water above natural ground level T7/1	T7/2
21st November 1966	0	Dry	
23rd November 1966	0	4 ft 2 in.	
27th November 1966	0·42 in.	4 ft 2 in.	
28th November 1966	0·13 in.	4 ft 6 in.	
1st December 1966	1·69 in.	14 ft 10 in.	1 ft 7 in.
2nd December 1966	0·14 in.	Dry	1 ft 11 in.
3rd December 1966	0·03 in.	Dry	1 ft 11 in.
4th December 1966	0·01 in.	Dry	2 ft 0 in.

A Casagrande type piezometer installed in borehole T3/1 (Fig. 1.1) at approximately the base of Tip 3 has remained dry since its completion on 1st December 1966.

Two Casagrande type piezometers have been installed in boreholes 9 and 14 (Fig. 1.1) which are sited on the slipped material near the back of the 1944 failure. Both piezometers are located at about the interface between tip material and natural ground. They indicate the piezometric level in this vicinity to fluctuate with reinfall from zero to a maximum of about 3 ft above the natural ground surface at piezometer 9. This piezometer is located on the course of the stream which is shown by the earlier Ordnance maps to have originated on the site now occupied by Tip 4.

The above piezometer observations indicate that the pore-water pressures in Tip 7 since the disaster have been low, the phreatic surface rarely rising more than a few feet above the level of the underlying natural ground. The slight seepage from the lower few feet of the tip into the excavation made south of the culvert in February 1967 was entirely consistent with these observations. The fact that the face of Tip 7 left by the disaster of October 1966 stood at an overall inclination of about 35°, little below the average ∅′ value of the tip rubbish, suggests that relatively low pore pressures also obtained within Tip 7 behind and above the position of the 'spring' at the time of that failure.

7 History of Tip 7

Basic information covering the history of Tip 7 is provided by the aerial and other photographs, by maps made from these photographs and by evidence given to the Tribunal. Reference may be made to the Report 'Interpretation of analyses of photography covering the Aberfan area' carried out by Fairey Surveys Ltd (Item 8).

Tip 7 was begun around Easter 1958. Initially the Tip 7 rubbish was placed over a small tip that had been sited between Tips 3 and 4 and used for a short time in 1944. The height of this small tip is uncertain but can be estimated to have been about 50 ft in the vicinity of the south-south-east extremity of the top of Tip 7, having had a top surface level of about +975 ft O.D. The top surface of Tip 7 was fixed at a level of +1050 ft O.D. near the inclined tramway and sloped gently to a level of +1035 ft O.D. at its south-south-east extremity. Thus, at this point, the top of Tip 7 was some 60 ft above the top of the small tip and about 115 ft above the natural ground.

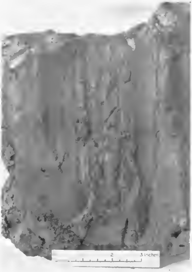
By April 1960, Tip 7 had advanced beyond the end of the small tip and had begun to encroach on to the clear ground beyond it. This clear ground, which is described in Fig. 2 of Fairey's report (Item 8), was tongue-shaped, its southern edge being outlined by the material from the flow of Tip 4 and its northern edge running along the toes of Tips 1, 2 and 3. The width of this tongue was about 130 ft and it sloped downhill. At this stage, the height of Tip 7 was, very approximately, 150 ft, i.e. a little in excess of the height of Tip 6, and the aerial photography (Fig. 5, Fairey Surveys Ltd) indicates no signs of instability.

By May 1963 (Fig. 6, Fairey Surveys Ltd), the condition of the tip had changed radically and a large depression, evidently caused by back-sapping, had appeared in the toe of the tip (Fig. 6, Fairey Surveys Ltd). This is shown even more clearly by Fairey Surveys Ltd, Fig. 7, which is the photograph of 14th September 1963. Both these aerial photographs have been used by the Ordnance Survey to produce photogrammetric contour maps. The contours on these show this depression and also indicate that a significant bulge had already been formed in the south-eastern toe of the tip.

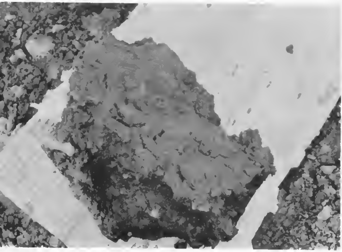
At this stage the back-sapping had already created a steepened face some 70 or 80 ft in height. The source of water causing back-sapping would appear to lie on a line between the issue of water shown on the 1957 Ordnance Survey to the south-east and final position of the spring to the north-west. It may be significant that the line joining the 1957 issue of water and 1966 spring lies parallel to the contours of mining subsidence illustrated in the reports by Wardell and Piggott (Item 6) and is thus in the direction across which tensile strains would be at their maximum. This also coincides approximately with one of the principal joint directions of the Pennant sandstone. The effect of tensile strains on a clay-covering of low plasticity over a jointed rock containing water under pressure is difficult to predict, but recent work on the cracking of the clay cores of earth dams suggests that open cracks may be caused by relatively low tensile strains (e.g. G.A. Leonards and J. Narain, 1963).

Evidence of a significant slip in the latter part of 1963 has been given to the Tribunal by the tipping gang. This slip appears to post-date the September 1963 photograph and probably occurred in the second half of October or the first half of November 1963. A major settlement of the front 30 ft of the crest of the tip is reported as having taken place at this time. The aerial photography supports the view that a significant movement of rubbish took place between September 1963 and November 1964 when the next low-altitude aerial photography was taken (Fig. 8, Fairey Surveys Ltd). From quantities evaluated by Hunting Surveys Ltd from the photography of September 1963 and November 1964 it appears that about 30,000 cubic yards of material had moved down on to the mountainside below the nominal toe of the tip between these dates (see Appendix 6). This estimate is approximate but clearly indicates that during this period the movement of material was more than a small run or slide of tailings.

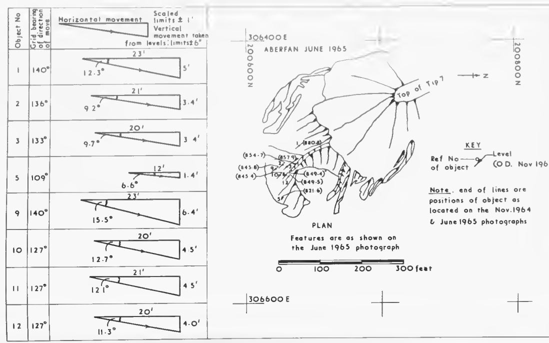
During the period November 1964 to June 1965, little new material appears to have reached the by then extended south-eastern toe (or claw) of Tip 7. Hunting Surveys Ltd have been able to identify a number of reference objects on these two successive air photographs and have plotted some of their positions in November 1964 and June 1965. Their displacements in the seven-month period which elapsed between these photographs are given on Fig. 1.11. It will be seen that these displacements form a consistent pattern and indicate a general downslope movement of the order of 20 ft in this seven-month period (an average of approximately 1 in. per day). The directions of these movements are found to correspond to the general direction of the striations observed on the slip surface exposed in this area in February 1967. The directions of the striations are plotted on Fig. 1.12. It may be noted that a large, flat-faced boulder of hard sandy siltstone, which was



1.10 Photograph of samples showing polished and striated slip-surface.

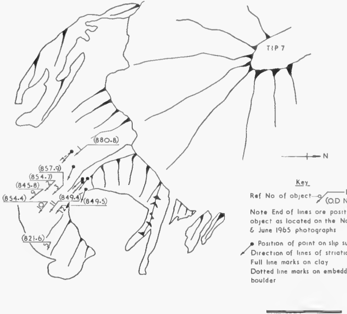


Colour transparency of a sample removed from above slip plane showing striations

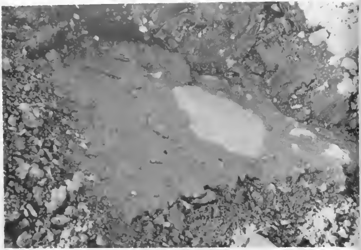


Object No	Grid bearing of direction of move	Horizontal movement	Angle	Vertical movement
1	140°	23'	12.3°	5'
2	136°	21'	9.2°	3.4'
3	133°	20'	9.7°	3.4'
5	109°	12'	6.6°	1.4'
9	140°	23'	15.5°	6.4'
10	127°	20'	12.7°	4.5'
11	127°	21'	12.1°	4.5'
12	127°	20'	11.3°	4.0'

1.11 Plan showing movements of reference objects between November 1964 and June 1965.


TIP 7
N
(880.8)
1
(857.9)
3
(854.7)
7
(845.8)
9
(854.4)
10
11
(849.4)
12
(849.5)
(821.6)
5
Key
Ref No of object
Level (O.D Nov 1964)
Note End of lines are positions of object as located on the Nov 1964 & June 1965 photographs
Position of point on slip surface
Direction of lines of striations
Full line marks on clay
Dotted line marks on embedded boulder
0 25 50 75 100 feet

1.12 Plan showing movements of reference objects between November 1964 and June 1965 and showing direction of striations on slip surface exposed by excavation, February 1967



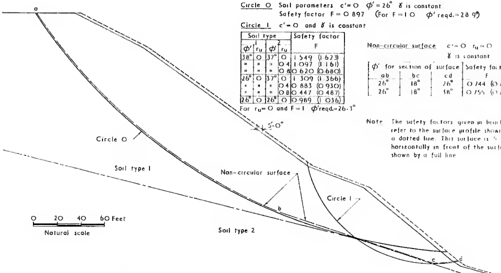
1.13* Colour transparency showing the embedded boulder with red pencil giving direction of striations.

1.14* As Fig 1.13 with red pencil showing direction of striations on adjoining slip surface

*Reproduced here in black and white

1.15* Colour transparency of slip plane exposed by rolling back material above it

1.16* As Fig 1.15.



Circle 0 Soil parameters $c' = 0$ $\phi' = 26°$ γ is constant
Safety factor $F = 0.897$ (For $F = 1.0$ ϕ' reqd. $= 28.9°$)

Circle 1 $c' = 0$ and γ is constant

Soil type				Safety factor
1		2		F
ϕ'	r_u	ϕ'	r_u	
38°	0	37°	0	1 549 (1 623)
"	"	"	0 4	1 097 (1 161)
"	"	"	0 8	0 620 (0 680)
26°	0	37°	0	1 309 (1 366)
"	"	"	0 4	0 883 (0 930)
"	"	"	0 8	0 447 (0 487)
26°	0	26°	0	0 989 (1 036)

For $r_u = 0$ and $F = 1$ ϕ' reqd. $= 26.3°$

Non-circular surface $c' = 0$ $r_u = 0$
γ is constant

ϕ' for section of surface			Safety factor
ab	bc	cd	F
26°	18°	26°	0 744 (0 754)
26°	18°	38°	0 755 (0 775)

Note The safety factors given in brackets refer to the surface profile shown by a dotted line. This surface is 5'-0" horizontally in front of the surface shown by a full line

1.18 Failure surfaces assumed for the stability analyses of Tip 7.

embedded firmly in the matrix beneath the slip surface at about 306483mE, 200635mN, had well-developed striations parallel, within observational error, to the 1964–65 displacement of the nearest reference object. The depth of fill at this point was of the order of 25 to 30 ft during this period and its slope was relatively flat compared with the face of the tip behind it, so that surface creep was likely to be small. The evidence suggests, therefore, that the 1964–65 movements resulted mainly from shear displacements on the well-defined slip surface exposed by the excavation of February 1967.

Profiles of the face of the tip at the various dates for which photogrammetric maps are available are plotted on Fig. 1.4. Critical parts of these profiles are shown in relation to the local geology in Figs. 1.5 and 1.6. From Fig. 1.5 it is apparent that by 1964 the surface of the tip material, in the depression formed by back-sapping, already lay some distance below the probable original ground level in that locality. As the thickness of the tip material at that point is not known, the depth of drift removed by 1964 cannot be determined accurately. It is clear, however, from Fig. 1.5 that much, and possibly all, of the drift overlying the Sandstone Rubble at that position had already been removed.

Further evidence in support of this is provided by the excavation of a trench, running some 150 ft downhill from the area of the 1966 spring, in which the contact between the tip material and the underlying drift was exposed. It was observed that, immediately over the broken surface of the drift, lay a deposit of fine-grained black material, generally several inches thick. This is similar in nature to the band of fine-grained black material found associated with the slip surface exposed at the foot of Tip 7 and probably also consists chiefly of degenerated shale of the type discussed in Section 5. It can be inferred from this that the removal of the original ground surface had taken place some years earlier, thus allowing this accumulation to form.

In 1965 it should be noted that the cliff behind the area of back-sapping still had a height of 80 to 90 ft, but was in a more forward position than at any previous time for which we have cross-sections. Its position prior to the disaster in 1966 is subject to some uncertainty but the examination by the Department of Photogrammetry and Surveying of University College, London, of a photograph taken in March 1966 suggests that the top of this cliff is still at much the same level, i.e. about 780 O.D., but that some further bulging of the tip has probably occurred, possibly of the order of 7 ft in magnitude in the plane of their observations.

A description of the events immediately preceding the disastrous slide on 21st October 1966 has been given in evidence and we would draw attention only to a few of the significant features. By the time the first members of the tipping gang reached the top of the tip at about 7.30 a.m. in the morning the crest had already sunk about 10 ft over a distance of 30 to 40 ft back from its edge. By approximately 8.30 a.m. this settlement had increased to around 20 ft. At about 9.10 a.m. the toe of the tip was observed to start moving forward and this movement continued for some minutes before the rapid flow of material down the hillside began. It should be noted from the cross-sections that an observer on the crest of the tip would probably have his view of the toe of the tip in the back-sapping area obscured by the top of the cliff at the back of this area and might well report movement of the top of this cliff as movement of the toe of the tip.

The subsequent flow of material down the hillside is described graphically in the evidence and its apparent fluidity is clear both from the evidence and from the manner in which it is shown by the photographs (Figs. 1.19, 1.20 and 1.21) to have spread across the hillside.

In the final slip some 140,000 cubic yards of rubbish were deposited on the lower slopes of the mountainside and in the village of Aberfan. The amount actually crossing the embankment is estimated, very approximately, to have been about 50,000 cubic yards.

The amount deposited in the village and on the lower slopes approximates to the amount of rubbish dumped in the period September 1963 to October 1966. The total amount of material which moved between the aerial photographs of June 1965 and October 1966 is clearly larger than the figure of 140,000 cubic yards, but much of it moved into positions previously occupied by tipped material or material from earlier movements, and its volume cannot be estimated with any accuracy.

The aerial photography prior to 1963 was from a high altitude and was not suitable for making accurate estimates of surface levels. Thus only a very approximate estimate of the quantity of rubbish already tipped by September 1963 is possible. The value obtained is 180,000 cubic yards, and may well be an underestimate. The total quantity of rubbish tipped at Tip 7 is thus of the order of 320,000 cubic yards.

The height in June 1965 from the highest point on the crest of Tip 7 (1036 ft O.D.) to nominal ground level at the toe of the tip on the line of the section of Fig. 1.4 is approximately 220 ft.

8 Discussion of mechanism of failure

Evidence as to the mechanism of failure on 21st October 1966 is provided by the composite picture built up from a number of sources. These are as follows:

(a) Evidence to the Tribunal by witnesses.
(b) Aerial and other photographs taken soon after the event and in the preceding years.
(c) An examination of the slip surface revealed by the October 1966 slip in the upper part of the tip and exposed by excavation in the lower part of the tip during February 1967.
(d) The results of soil tests on the foundation materials, the tip material in its random state and on samples of the slip surface.
(e) The hydro-geology of the site.
(f) Stability analyses carried out on the tip profile together with an examination of the movement into the excavation carried out in February 1967.
(g) Model tests carried out both at Imperial College and University College of Swansea.

An examination of this evidence indicates that the movements on 21st October 1966 commenced as the re-activation, consequent on rise of water pressure at the base of the tip, of the sliding movements on a pre-existing shear surface largely created by movements in earlier years. This rise in water pressure followed heavy but not unusually high rainfall.

The large magnitude of these initial shear displacements caused a major part of the sliding mass of colliery waste to degenerate into a flow slide. This secondary phase of the failure owed its occurrence to the presence of a substantial volume of loose, saturated material at the base of the tip above which lay a large volume of loose, wet material containing only a small percentage of air in its voids. The saturation of the base of the tip was caused primarily by water issuing from the ground in the absence of free drainage of the base of the tip. The flow slide was the primary cause of damage to the Junior School.

The removal of tip material and some natural ground in the initial stages of the slide released a quantity of ground water[1] which, although large compared with normal spring flows was, when first observed, considerably less, for example, than the estimated initial flow of the burst 31-in. water main in the disused canal.[2] This release of ground-water brought down more colliery rubbish in the form of 'mud-run' and extended the area of damage. This mud-run together with water from the burst water mains in the disused canal hampered the initial rescue operations.

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[1] Evidence by J J D Bowen and P M Grant. About 20 cu ft /sec at mid-day on 21st October 1966.

[2] Evidence by C J Jones, Divisional Engineer of the Taf Fechan Water Board. About 70 cu ft /sec. immediately after the burst, falling to 30 cu ft /sec after 10 minutes.

The evidence for movement on a pre-existing failure surface is based on the following:

(i) The displacements of identifiable reference objects on the surface of the south-eastern toe (or claw) of Tip 7 in the period November 1964 to June 1965 have been determined from maps prepared by Huntings Surveys Ltd, as indicated in Section 7. These movements were in general of the order of 20 ft.

(ii) The excavations made in February 1967 to the south-east of the 'spring' (see Fig. 1.1) revealed a polished and striated slip surface. A sample of this surface has already been illustrated in Fig. 1.10. Other illustrations are given on the transparencies, Figs. 1.13–1.17 (reproduced here in black and white).

A large flat-faced boulder of hard sandy siltstone embedded firmly in the matrix beneath the slip surface is shown in Fig. 1.13. The surfaces of the boulder showed well-developed striations and, as indicated by comparison of Figs. 1.11 and 1.12, these are in the direction indicated by the data from Huntings Surveys Ltd for the 1964–65 movements. The striations in the adjacent clay (Fig. 1.14) were directed in plan about 15° more in the downslope direction (see Figs. 1.11–1.12). Figs. 1.15 and 1.16 show other areas of the slip surface, which lay within a well marked black band of tip rubbish having a matrix of clay and silt-sized particles. The thickness of this band varied from about 1 in. to 12 in. The slip surface was located generally about $\frac{1}{4}$ in. above the base of the band. In places the black band could be uncovered by brushing off the overlying, more granular tip material. The major part of the black band could then be rolled off as a whole, as shown in Figs. 1.15–1.16, to expose the slip surface immediately below it. Fig. 1.17 shows a lump of the fine matrix material taken from just above the slip surface.

In the southern part of the area examined the striations dipped in a south-easterly direction. The material below the slip surface here appeared to be Tip 7 material at higher levels, material forming part of the flow from Tip 4 as the ground surface was approached and finally the sandy Head, and in places possibly the Boulder Clay, forming the natural ground. The tip material below the surface was in general more compact than the material sliding over it.

(iii) When the excavation was made, the resulting reduction in toe support led to a further renewal of movement on this pre-existing slip surface. The formation of this surface clearly predated the excavation. Measurements showed the rate of these movements to be of the order of 1 in. per day. No other surfaces were detected and the trace of the crack produced in the face of the remaining part of Tip 7 by this movement was in conformity with the back of the slip surface revealed by the slide of October 1966.

(iv) The residual angle of internal friction $\varnothing_r'$ measured on an undisturbed sample taken across this slip surface, was found to be only $18\frac{1}{2}°$ in a fully drained test. Scrapings from the striated surface gave a residual $\varnothing_r'$ value of $17\frac{1}{2}°$. This is to be compared with values of $\varnothing'$ at small strains in fully drained tests of 38° to 40° for the random tip rubbish and 31° to 32° for the tailings.

It is thus easier for a movement to continue on a failure surface once an appreciable deformation has occurred than for a new surface to be created. This mechanism has clearly operated in this case.

(v) Two large areas of slip surface were exposed by the October

1966 slip not far below the crest of the tip and were examined in early November 1966. These areas were backed by a very compact matrix of fine material in which particles of shale and pieces of wood were embedded. The shale particles and wood were aligned approximately parallel to the surface pointing down the slope. No striations were apparent in the clay matrix but the surface had been exposed to heavy rain before our first inspection. Downslope striations were observed on some of the shale particles embedded in the slip surfaces.

The surfaces were standing at slopes of 40° to 50° and remained stable for about one month in spite of the loose character of the bulk of the tip rubbish. It may therefore be inferred that they were not newly formed by the October 1966 slide.

(vi) Analyses of the stability of the remaining part of the tip which moved towards the excavation made in February 1967 gave an average value of angle of internal friction required for stability of only 26 , on the assumption that pore-water pressures on the failure surface were negligible. This assumption is justified by the observations referred to in Section 6. Details of these analyses are given in Appendix 4.

(vii) The stability analyses of the central section of the tip based on the 1965 profile (Fig. 1.18) shows that a deep slip surface passing behind the crest of the tip would require an average value of the angle of internal friction of 29° to 30° to give a factor of safety of 1·0, assuming pore-water pressures to be zero. This is much below the value of 38° to 40° for the random tip rubbish.

The pore-water pressure required over a limited area (Fig. 1.18) to cause failure on a fresh slip surface of this shape would be approximately 60% of the total weight of the material above the toe. A pore pressure of this magnitude seems improbable from the hydro-geological study, and would, in any case, cause a failure of the toe of the tip (Fig. 1.18) before a deep-seated failure resulted.

(viii) Evidence given to the Tribunal by the tipping gang suggests that the rear of the slip surface in the crest of the tip had remained in a more or less constant position since 1963, and that intermittent settlements occurred in front of this line.

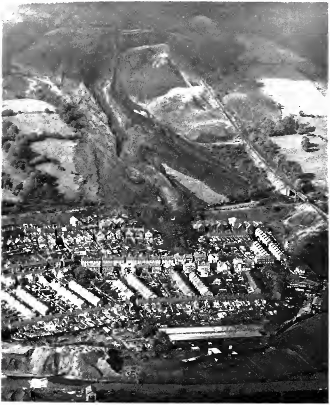
(ix) The model tests both at Imperial College and University College of Swansea (Appendix 5) show that a mechanism of failure corresponding to that observed, i.e. the sinking of the crest of the tip associated with an outward movement of the toe, could only be reproduced if a pre-existing discontinuity was introduced into the model at the base of the tip and water pressure applied beneath this discontinuity.

On the basis of this evidence we conclude that *the initial phase* of the disastrous slip on 21st October 1966 consisted primarily of a reactivation of movement on the pre-existing shear surface.

The evidence for *the second phase* of the slip having taken the form of a flow-slide is as follows:

(1) The toe of the tip broke away and travelled down the mountainside at a considerable speed (probably between 10 and 20 miles per hour) followed by a large quantity of material having an apparently fluid consistency.

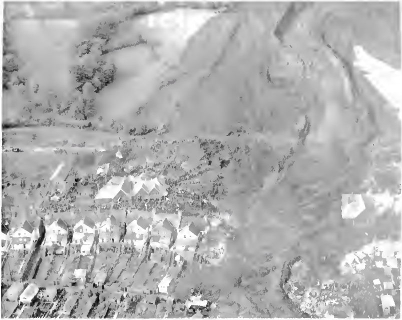
(2) An examination of the photographs (Figs. 1.19 to 1.24) suggests that flow-slide material, i.e. material which has become 'fluid' due to the transfer of load on to the water already contained in its pore space, formed the initial phase of the flow of material which formed two branches on either side of the bare strip of land above the Senior School. The southern branch of this fork appears to have been primarily responsible for the destruction of the Junior School (Fig. 1.21).



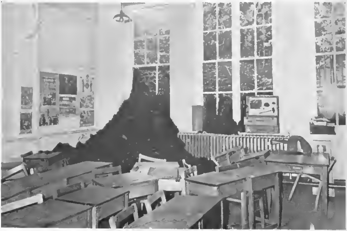
1.19 Photograph showing general view of flowslide and mud run. 21st October 1966, approx. 1 p.m.

1.20 [illegible]

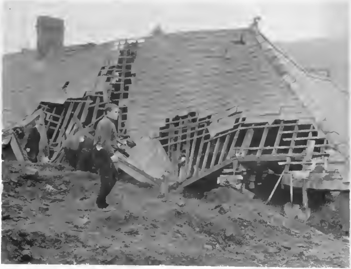
1.22 [illegible] 'dry' mixture of rubbish [illegible]



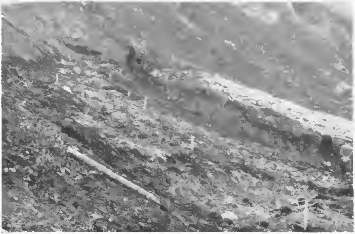
1.21 Photograph giving [illegible] 21st October 1966 approx. [illegible] p.m.



1.23 Photograph showing a mound of rubbish in the corner of a classroom in the Senior School with no indication of free water.



1.24 Photograph showing rubbish at rear of Junior School at approximately 3 30 p m on 21st October Person in light-weight shoes is able to walk across this material without difficulty



1.25* Colour transparency showing bowl in natural ground left by the slip The pegs mark original ground surface

(3) The photographs showing the state of some of the material at the toe of the flow-slide indicate that it travelled without any great excess of water (Figs. 1.22 and 1.23). Fig. 1.24 indicates that within a few hours some areas of material were relatively dry and could be walked on without difficulty.

(4) Figs. 1.19, 1.20 and 1.21 suggest that the 'mud-run' associated with the outflow of water which followed the flow-slide was confined to the central area of the slide.

(5) Flow-slide phenomena result from the transfer of the load initially carried by the solid skeleton of the material on to the water in the pore space. In the case of a slide on a slope such as that at Aberfan, i.e. approximately 12½°, the percentage of load which needs to be carried by the pore-water for a slide to take place is much less than on a flatter surface. For a value of the angle of internal friction of 38° this percentage would have to be 72%. For a value of the angle of internal friction of 32° (e.g. as in the tailings or in the finer material) the percentage would have to be 64% and for a value of the angle of internal friction of 18° the percentage need only be 32%. Loose, saturated material could thus flow without difficulty and loose material containing a percentage of air in the pore space could also flow under these conditions.

A full discussion of a major flow-slide has been given by Professor Arthur Casagrande in the 1965 Terzaghi Lecture entitled, 'The Role of the "calculated risk" in Earthwork and Foundation Engineering'. In an appendix to the lecture, Casagrande quotes the work of Hazen (1920) who discussed the possible relationship of this phenomenon to the crushing of the granular structure of soft rocks.

The third phase of the slip took the form of 'mud-run' resulting from the addition of water to the tip debris, in general, after it was already in motion. This 'mud-run' is illustrated in Figs. 1.19–1.21.

As has been mentioned earlier, the water content of a small 'mud-run' occurring during a period of heavy rain at the beginning of December 1966 averaged about 14%. The colliery rubbish is thus very clearly susceptible to flow with the addition of water. The estimated initial flow of the 'spring' revealed at the toe of the tip after the flow of material had largely ceased was 20 cu ft/sec.[1] Although greatly in excess of the normal flow of the 'spring' of about 0·1 cu ft/sec, this value is appreciably less than the initial flow estimated for the burst 31-in. water main in the disused canal.[2]

From an examination of Figs. 1.19, 1.20 and 1.21 and on the basis of observations of the December 1966 'mud-run', the deep channel eroded in the upper part of the material appears to have been eroded by the 'mud-run' itself rather than by the flow of water from the 'spring'. (The form of the lower part of the 'mud-run' is consistent with this view.)

No objective criteria exist for determining the relative amounts of damage caused by the flow-slide, the subsequent 'mud-run' and the water from the burst water mains in the disused canal. An examination of the photographs, however, strongly suggests that the flow-slide was the primary cause of the damage to the Junior School and to the houses between the Junior School and the Senior School. The area of damage was clearly extended by the 'mud-run' and, to a limited extent, by additional water from the burst water mains.

The development of an issue of water or spring from the area in which the 'spring' was finally seen to emerge is linked with the history of previous movements in this area of the base of the tip. The amount of definite evidence is very limited, but, as has been mentioned in Section 7, it is apparent that water was issuing from this area by May 1963 and was resulting in back-sapping on a large scale. By November 1964 the cross-sections (Figs. 1.4 and 1.5) indicate that some of the drift overlying the water-bearing layer of Sandstone Rubble had already been removed. The fact that the lag between the slip of 21st October

[1] [2] See footnotes on p. 50

1966 and the preceding period of heavy rainfall corresponds approximately to the lag between the flow of the present 'spring' and a preceding period of rain suggests that the base of the slip was directly influenced by water from the underlying Pennant sandstones.

The development of the 'spring' in its final position on 21st October 1966, almost certainly resulted from the removal of a further part of the drift mantle after the initial movement of the slip had begun. Whether this occurred during the initial stage of the slip or during the subsequent stage of rapid collapse is difficult to establish. If the former were the case, additional water from this source would have assisted in the saturation of the lower part of the tip, which is one of the prerequisites of a flow-slide. On the other hand, the shape of the surface of the actual ground exposed immediately adjacent to the 'spring' by the excavation made in February 1967 (Fig. 1.25) is more consistent with a slip surface having in section a smaller radius, such as the toe circle shown on Fig. 1.18.[1] This would, however, have resulted in the release of additional water in the tip material only after the first stage of the slip had been completed.

In considering the quantity of saturated material involved in the slide it is to be borne in mind that the quantity of tailings and slipped material from the area of back-sapping and from the 1963 slip and flow-slide, estimated at some 30,000 cubic yards, already lay on the mountainside immediately below the toe of the tip, and much of this material would have been in a condition approaching full saturation.

The formation of the slip surface which already existed in October 1966 is the result of the previous history of sliding of Tip 7. The large movements on this surface have been accentuated by the tipping of material at the crest and removal of material at the toe by back-sapping.

The history of Tip 7 summarised in Section 7 indicates that major movements were occurring in the period 1964–65 and that a slip having the same rear scarp position as the 1966 slip had occurred in October or November 1963. The aerial photographs suggest that even before this slip, which was of considerable magnitude, the lower part of the tip to the south-east and south had already bulged due to shear failure within the tip or the material forming its foundation.

The stability analyses presented in Appendix 4 suggest that with the average values of angle of internal friction found in the drift foundation, the factor of safety would be low but that actual failure would be unlikely unless small values of pore-water pressure were present in the foundation. It must, however, be noted that the date at which failure probably first occurred differs little from the date at which tailings were first dumped on Tip 7. If an apron of tailings had formed at the toe of Tip 7 on which additional rubbish was tipped their lower angle of internal friction and low permeability would have rendered them a less satisfactory foundation than all but the poorest of the drift material. The introduction of tailings into Tip 7, therefore, cannot be ruled out as a factor associated with an initial failure of the tip before that of 1963.

It should also be noted that the angle of internal friction of the finer material associated with the slip surface was found to depend on the pressure at which it was tested and, when sheared in a direction not corresponding to a pre-formed slip surface, varied from 35° to 20° as the pressure was increased (see Appendix 3). This suggests that zones of degraded material formed by minor slipping at the toe may assume greater significance as the height of the tip is increased and may partly account for the fact that both Tip 7 and Tip 5 developed distinct bulges on their south-eastern sides at much the same height (an undeformed slope of more than about 160 ft in height appears to be rare).

The development of the slip surface has thus most probably been the result of a succession of failures of which the 1963 failure in moving along a continuous deep slip surface approximated most closely to the 1966 slip.

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[1] This shape could also have been formed by erosion of the drift as material slid down to form the 'mud-run'.

It is of interest to note that Tip 2, whose base may be particularly well drained and largely free of excess pore pressure, is in fact standing to a height of 200 ft without any significant sign of deformation on the slope. This may indicate that the margin between the initiation of instability and apparent complete stability may depend very critically on the effectiveness of the drainage at the base of the tip. It should also be noted that the slope of the face of this tip is approximately 30°. The stability analyses given in Appendix 4 show the important effect of flattening the slope on the value of the factor of safety.

9 Conclusions

1 Tip 7 at Aberfan had been unstable and intermittently sliding for a number of years prior to the final failure which caused the disaster of 21st October 1966. These slips were deep-seated and are not to be confused with runs of tailings.

This conclusion is based on the following evidence:

(a) The displacements of identifiable objects on the surface of the south-east toe of Tip 7 (or claw) between November 1964 and June 1965 have been determined from plans made by Huntings Surveys Ltd from aerial photographs. The majority of these displacements were of the order of 20 ft in plan over a seven-month period.

The displacements are taken to be the result of deep-seated shear movements since an extensive excavation in this area has revealed a polished and striated slip surface such as would be produced by a very large shear displacement. The directions of the striations are in the same general directions as the movements obtained from the aerial photography.

It was noteworthy that a large flat-faced boulder of hard sandy siltstone embedded firmly in the matrix beneath the slip surface had developed striations parallel in plan, to within observational error, to the 1964–65 displacement of the nearest reference object. The striations on the surface of the adjacent matrix of fine grain material, which would tend to represent the final rather than the long-term movement, were orientated more towards the valley bottom by an angle of about 15°. The depth of fill at this point was of the order 25–30 ft during the 1964–65 period referred to. Its slope was relatively flat compared with the face of the tip behind it, so that surface creep was likely to be small.

(b) The occurrence of a slip accompanied by a flow-slide of tip rubbish for a distance of over 700 ft down the mountainside in the latter part of 1963, probably late October or early November, is supported by evidence from the tipping gang. The occurrence of such a slip between September 1963 and November 1964 is confirmed by a comparison of the relevant aerial photographs.

Though the flow of material down the mountainside resulting from this slip may have been small[1] as compared with the final flow in October 1966, the statements that the cut-back at the crest was about 30 ft and that the slip surface formed on this occasion has persisted as the dividing line between the stable and unstable parts of the tip are compatible with the strength characteristics of this material as revealed in the later stages of the investigation. These statements are also compatible with the crest position of the tip indicated by the maps made from the aerial photographs of 1963, 1964, 1965 and 1966.

(c) An examination of the September 1963 aerial photographs, together with the map and sections based on them, indicates that back-sapping (or the removal of material from the toe by an issue of water or a spring leading to intermittent slips of progressively increasing size) was already well advanced at this date, and that the material having a relatively flatter surface to the south of the area of back-sapping can only have reached that position by slipping.

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[1] This is a relative term. P.M. Grant (p. 2211 of the Transcript) stated that the Tymawr slip involved about 1000 tons. The 1963 slip was on a larger scale, the total volume of material passing the nominal toe of the tip between September 1963 and November 1964 being approximately 30,000 cubic yards or 40,000 tons

(d) Evidence from the sections prepared from the 1963, 1964, 1965 and 1966 maps and witnesses' accounts of the slip shows that just before the tip slipped in October 1966, the crest position approximated to that of September 1963.

2 For much of the time that sliding has been occurring, the movement has been taking place mainly along the same slip surface. This conclusion is based on the following evidence:

(a) When the excavation was made in February 1967 to the south of the present 'spring' position, a single well-striated slip surface was discovered. At all points examined the slip surface was associated with a distinct layer of fine tip material generally from 1 in. to 12 in. in thickness. The striations cut in the hard sandy siltstone boulder embedded in the lower surface indicated that large displacements had occurred. The directions of these were in conformity with the 1964–65 movements of the overlying tip determined from the aerial surveys. The tip material below this surface was in general more compact than the material sliding over it. In the southern part of the area examined the material below the slip surface appeared to be Tip 7 material at the higher levels, Tip 4 slip material as the ground surface was approached and finally the drift forming the natural ground.

(b) When the excavation was opened the relative movement across this slip surface was found to be of the order of 1 in. per day. No other surfaces were detected. The trace of the crack produced on the face of the remaining part of Tip 7 by this movement is in conformity with the back of the slip surface revealed by the slide of October 1966.

(c) The residual angle of internal friction, $\varnothing_r'$ measured on an undisturbed sample taken across this slip surface, was found to be only $18\frac{1}{2}^\circ$ in a fully drained test. Scrapings from the striated surface gave a residual $\varnothing_r'$ value of $17\frac{1}{2}^\circ$. This is to be compared with values of $\varnothing'$ at small strains in fully drained tests of 36° to 40° for the random rubbish and 31° to 32° for the tailings.
It is thus much easier for movement to continue on a failure surface once a large deformation has occurred than for a new surface to be created.

(d) Two large areas of slip surface were exposed by the October 1966 slip not far below the crest of the tip and were examined in early November 1966. These areas were backed by a very compact matrix of fine material in which particles of shale and pieces of wood were embedded. The shale particles and wood were aligned approximately parallel to the surface, pointing down the slope. No striations were apparent in the clayey matrix but the surface had been exposed to heavy rain before our first inspection. Downslope striations were observed on some of the shale particles embedded in the slip surfaces. The surfaces were standing at slopes of 40° to 50°, and remained stable for about one month in spite of the loose character of the bulk of the tip rubbish. It may therefore be inferred that they were not newly formed by the slip of October 1966. Thus, both the surfaces examined in November 1966 and in February 1967 are considered to be part of a common slip-surface and to pre-date the October 1966 slip. These are in conformity with tipping gang's references to a line of weakness persisting since the 1963 slip.

3 The origin of this slip surface and the source of the more clay-sized

material which gives it a low residual angle of internal friction are matters which call for very detailed consideration.

During the period February 1962 to December 1963, the output of tailings from Merthyr Vale Colliery is reported as having been included in the rubbish tipped. Also by September 1963 there is evidence from aerial photographs that active back-sapping was occurring and that the toe of the tip had therefore advanced over a substantial issue of water or spring. Both factors would have contributed to the first significant slip in the tip.

The extent to which the clay-sized material in the immediate vicinity of the slip surface is derived from the degradation of shales in the tip rubbish by the large relative movement of the surfaces, by the smearing of existing fines and tailings, or by other causes is currently being examined. Present evidence indicates that degradation of the shale and segregation of the fines provide the most likely explanation. The continual addition of material to the crest of a tip which is settling due to movement on a shear surface is a most effective way of ensuring large displacements along this surface. Removal of material from the toe by back-sapping has a similar effect.

4 The pre-existence of a slip surface along which a reduced angle of friction is operative means that fresh movements would be initiated by a much smaller rise in pore pressure, or by a much smaller steepening of the toe by back-sapping, than would be the case in an intact and stable tip.

This is consistent with the evidence that intermittent settlements of the crest occurred during the three years prior to the final failure.

This also is consistent with the indication from model tests, that to cause, in an otherwise stable tip, a failure having a sequence of events similar to that observed at Aberfan would require much higher water pressures than appear compatible with the hydro-geology of the site.

5 Water has contributed to the disastrous slip of October 1966 in four principal ways:

(1) Water issuing beneath the tip has caused back-sapping and led to recurrent movements over the years since 1963.
(2) Water under pressure acting in the tip material and in the limited area of the foundation where the slip surface was adjacent to the natural ground reduced the effective stresses in the fill and initiated a shear displacement. In view of the presence of pre-existing slip surface, this pressure need not have been very large.
(3) Water filling (or nearly filling) the voids of the loose fill comprising the tip and covering the area of mountainside below it made it susceptible to a catastrophic flow-slide since a shear displacement or shock wave[1] could result in the transfer of most of the load on to the relatively incompressible water in the voids, thus reducing the frictional strength to a very low value.
(4) Water released by the slip and consequent flow-slide caused a 'mud-run' of tip rubbish.

Rain water percolating directly downward through the tip increases its degree of saturation, but does not lead to an excess pore pressure unless it is impeded by a less pervious layer. The rate of percolation is in any case slow in material of this grading. Piezometers (pore pressure gauges) installed in the tip material after the disaster showed no significant pore pressures in the remaining part of Tip 7, nor did they in general show any significant response to rainfall.

6 The shape of the area of back-sapping mapped from the September 1963 aerial photographs strongly suggests that the chief source of water causing it was not the issue of water shown on the 1957

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[1] Correspondence with the U K A E A suggests that seismic disturbance can be ruled out in the present case.

Ordnance Survey, but was, at that date, mainly from a location closer to the position of the spring revealed by the October slip.

The section of Fig. 1.5 suggests that by 1964 the action of back-sapping and the associated slipping had already removed the upper part of the drift mantle which forms the natural ground surface in this area. The release of underground water from this area would in consequence have been facilitated.

7 The information now available to us indicates the following sequence of events on 21st October 1966:

(a) Overnight the rise in water pressure in the ground immediately beneath the tip and in the lower part of the tip re-activated sliding movements on the pre-existing slip surface. A slow outward movement on the toe took place accompanied by a 10 ft settlement of the crest. This settlement was observed by the tipping gang to have taken place by about 7.30 a.m.

(b) This settlement increased to about 20 ft by about 8.30 a.m. The accompanying shear strains in the lower and most saturated part of the tip were by this time approaching the critical condition for a flow-slide.

(c) The flow-slide commenced in the central steep section of the toe of the tip at about 9.10 a.m. After the initial slow movement, the flow-slide accelerated down the mountainside to the village, taking with it saturated material lying downslope from the tip. Following on, and possibly carried by, this semi-fluid material, the bulk of the slightly less wet tip material slipped down, removing in the process both tip material and drift to release the water impounded in the fissured sandstone.

(d) The estimated initial flow of water from the vicinity of the spring thus formed (based on the evidence given before the Tribunal) was of the order of 20 cu ft/sec and is compatible with the size of the open joints of fissures identified by raking boreholes in this area. This led to a 'mud-run' which carried down more material, which extended the central part of the flow-slide further into the village and finally scoured a deep channel in the flow-slide material (i.e. the deep channel was scoured by the 'mud-run' rather than by water). On the basis of evidence from Bowen and Grant it must be assumed that part of this flow initially came from a source behind the present spring position, which ceased to operate as the water level fell. Bad weather has delayed attempts to expose this particular area.

8 It is difficult to establish objective criteria for assessing how much of the damage was due to the initial flow-slide, how much was due to the subsequent 'mud-run' and how much to the additional water released by the fracture of the two water mains in the canal behind the railway embankment.

An examination of the various photographs and the statements of witnesses about the consistency of the material and of the depth to which it accumulated after passing over the embankment, suggest that the flow slide was the primary cause of the destruction, in particular of the Junior School.

This view is supported by a detailed examination of the evidence from the Abercynon flow-slide in 1939, which was not accompanied by a significant outflow of water but was as potentially destructive as that at Aberfan in 1966.

9 For a tip whose face is defined by a constant slope angle, geometrically similar slip surfaces will embrace a volume of soil per unit breadth of slip which depends on the square of the height. Since the breadth of a slip is likely to be roughly pro rata with its height, the volume displaced will depend approximately on the cube of the height. The potential energy of this mass will depend on its mass multiplied

by the height of its centre of gravity, which is also in direct proportion to its height. Thus for a given density the potential energy will depend on the fourth power of the height from the crest to the toe, quite apart from the slope below it.

Thus if the height of a tip is doubled, the mass moving in a slip may be multiplied by a factor of about 8, and the potential energy available may be multiplied 16 times. Height is therefore an important factor in the destructive ability of a tip.

10 In tips of soft rocks such as shale, the greater stresses in high tips may lead to crushing at inter-particle contacts and make the lower saturated layer more susceptible to flow-slide phenomena. It is noteworthy that the slips at Abercynon in 1939, Aberfan Tip 4 in 1944 and Aberfan Tip 7 in 1966 occurred when the crest-to-toe vertical height was of the order of 200 ft.

11 Tips constructed at a slope angle or angle of repose which approximates to the angle of internal friction ϕ' have, even in the absence of excess pore water pressure, a very low factor of safety against sliding on relatively deep surfaces. For example, a surface tangential to a base slope of 1 in 4 and cutting back 30 ft at the crest for a crest-to-toe vertical height of 200 ft has a factor of safety of 1·15.

The factor of safety is reduced by building on a foundation having a lower value of angle of internal friction, particularly if steeply sloping. It is also reduced by the presence of pore-water pressure in the foundation or tip rubbish.

Factors of safety of this order are much below those called for in other structures whose failure could be potentially destructive. These low factors do not include any allowance for long-term deterioration of the material. However, flow-slide phenomena appear to have been limited to active tips. This aspect of the problem requires more detailed study and it will be one of our recommendations that the question of acceptable risk should be reviewed by an appropriate Committee.

12 Flow-slides occur only in loose cohesionless materials. The density at which flow-slides will occur increases with pressure and thus with the height of the tip. According to Casagrande (1965), no precise dividing line can yet be drawn between materials which will flow and materials which will not. The trigger mechanism and the slope of the ground over which the flow-slide is to travel are controlling factors. However, flow-slides in compacted materials are highly improbable.

The full saturation of a loose granular material makes it most prone to move as a flow-slide. This emphasises the importance of drainage in tips of loose materials. However, it is also clear that loose partly saturated material can 'flow' if the gradient is sufficient. The 'flow' of powder snow in an avalanche is an example of this phenomenon.

For complete safety, therefore, attention has to be given both to compaction and to drainage.

13 The principal lesson to be learned from this disaster is that large tips of colliery rubbish (or indeed of any type of spoil) have to be treated as engineering structures. The procedures of site investigation and control customary in other fields of civil engineering should thus be applied.

Our detailed recommendations are given below.

Summary of Conclusions

A rise in pore-water pressure at the base of the tip due to an increase of pressure in the water in the fissures of the Pennant sandstone following heavy but not unusual rainfall reactivated sliding movements on a shear surface created mainly by movements in earlier years.

The large magnitude of this displacement caused a flow-slide to commence due to the presence of a substantial volume of loose, saturated material at the base of the tip and of a large volume of loose, wet material, containing only a small percentage of air in its voids, above it. The saturation of the base of the tip was primarily caused by water issuing from the ground in the absence of free drainage at the base of the tip. The flow-slide was the main cause of damage to the Junior School.

The removal of tip material and of some natural ground by the two initial stages of the slide released a quantity of water, which, though large compared with normal spring flows, is estimated to have been only 20 cu ft/sec at mid-day on the day of the disaster. This release of ground water brought down more rubbish in the form of a 'mud-run' and extended the area of damage. This 'mud-run', together with water from the burst water mains in the disused canal, hampered the initial rescue operations.

Recommendations

1 Large or potentially dangerous tips of colliery rubbish (or of other industrial waste or spoil) should be considered as engineering structures. The procedures of preliminary site investigation and control during placing, customary in other branches of civil engineering should be applied.

2 The initial site investigation necessary for a new tipping area or for the extension of an existing tip complex should be under the direction of a civil engineer experienced in the field of soil mechanics. The civil engineer should be responsible for seeking the advice, when necessary, of a geologist familiar with the local stratigraphy.

3 To ensure that only suitably qualified engineers are employed for the purpose specified in paragraph 2, a panel of approved engineers should be established by the appropriate Ministry on lines similar to those of the Reservoirs (Safety Provisions) Act of 1930 (as amplified in the Report on Reservoir Safety published by the Institution of Civil Engineers in 1966). It may be noted that some lagoons for the disposal of fly ash are already constructed to the requirements of this Act.

4 The principle of regular statutory inspection by an independent qualified engineer should be extended to large or potentially dangerous rubbish tips.

5 It appears from the present investigation that catastrophic flow-slides as at Aberfan and Abercynon, and the failure of lagoons of tailings as at Tymawr and Williamthorpe, are associated with active tipping operations. The frequency of the independent inspection of active tips should be at least once per year, decreasing, as recommended by the inspecting engineer, to once in, say, 10 years for old tips.

6 The present investigation has been concerned primarily with the causes of the failure of one particular tip rather than with the examination of the possible hazards involved under other geological conditions, with rubbish or tailings of different geological origin, placed by other methods.

We therefore recommend that a Tip Safety Committee be set up by the appropriate Ministry to report, *inter alia*, on:

(a) The standards of safety which should be called for in large tips adjacent to inhabited property, to public highways and to railways, etc; and whether or not lower standards should be accepted for tips at present more remote from developed areas.
(b) The definition of a large or potentially dangerous tip for statutory purposes.

The Committee should also make recommendations on:

(c) Which of the observations and investigations begun during the present Inquiry should be continued, under the sponsorship of the National Coal Board, the Science Research Council or the National Environmental Research Council. Obvious examples are long-term observations of the effect of rainfall on ground-water level, and further studies of the degradation of shale rubbish after tipping and the influence of this process on the strength and drainage of the tip.

(d) What other lines of investigation should be followed up, involving either field observations or laboratory investigations relevant to the safety aspects of both new and old tips.
These investigations might include studies of the feasibility of applying to waste tips the techniques of controlling ground-water level by relief wells and of controlling pore pressure in the fill by drainage layers currently used in the construction of embankments.

(e) What hazards, if any, are involved in the present methods of disposing in bulk of other similar industrial waste products.

APPENDIX 1

Summary of paper 'Landslides in South Wales' by Professor George Knox

Summary of paper on:

'Landslides in South Wales Valleys', by Professor George Knox, FGS, MIME. Read and discussed in Cardiff, 29th March 1927. Further remarks and discussion in Cardiff on 28th April 1927.

All published in *Proc. S. Wales Institute of Engrs,* **43**, 161–233, Discussion, 234–247; **43**, 257–267, Discussion, 267–290.

Scientific background

The main stimuli behind the paper appear to be the books of the geologist Heim (1882) and the geomorphologist Penck (1894), both published in German.

Although writing two years after the publication of Terzaghi's *Erdbaumechanik,* Knox appears to be quite unaware of the principle of effective stress and rejects (p. 290), a suggestion by one of his audience (Mr R. James, p. 284) in which this principle is implicit. For his applied mechanics, Knox appeals only to Rankine (1857) and 'Boussinesq' (actually Coulomb, 1776) and to early American work on the Panama Canal slides. It is perhaps significant that the most recent of the papers quoted in the bibliography to Knox's paper was published 11 years earlier, in 1916. The rest of the bibliography is of pre-1914 date.

Knox's paper was thus, at least with respect to its theoretical aspects, out of date when it was written.

Objectivity

Although the author rightly stresses the widespread occurrence of natural landslides in the Welsh mining valleys, he appears to lack objectivity in attempting to establish that 'the weight of a colliery tip has nothing whatever to do with initiating a landslide' (p. 181). This view is maintained despite inclusion in the paper of five case records of landslides involving colliery tips (Cwm, pp. 206–209; Blaina, pp. 209–211; Pentre, 1916, pp. 211–218; Pentre, pre-1916, pp. 218–219; Pochin, pp. 260–264), probably because Knox is incorrect both in his theoretical treatment of the failures (pp. 180–182) and in ascribing their physical mechanism to 'underground mud streams' (p. 221). Of such failures it is stated (p. 229) that 'if a colliery tip . . . rests on soil or rock liable to slide, it must slide with them, but it is in no way responsible for causing the slide'. In the case of the 1916 slide at Pentre the claim is made, in support of this view, that when the rock beneath the tip gave way it moved 'faster than the colliery refuse riding on it' (p. 216).

In the case of the landslide at New Tredegar (p. 194), the Brecon and Merthyr Railway Company is commended for removing large quantities of debris from the toe of a landslide, a practice which is rightly discouraged elsewhere in the paper (pp. 172, 188, 228–229).

Valuable features of paper and discussion

Despite the shortcomings indicated above, Knox's paper contains much that is of value. The full discussion and the demand for a second meeting show that a considerable awareness of and interest in landslide problems existed amongst engineers in South Wales in 1927, and that through qualitative experience some valuable conclusions had already been reached.

The chief of these are:

A *Technical principles*

(i) Recognition of the over-riding importance of water in causing landslides (pp. 168, 172, 177, 188–190, 193, 197, 203, 206, 211, 213, 221, 228 and 266; Discussion, pp. 242, 243, 275, 283 and 284).

(ii) Recognition that, in South Wales, most of the water concerned in a landslide is derived by percolation from the joints of the Pennant sandstone rather than from direct rainfall on the slide area (pp. 173, 243).

(iii) Recognition that in South Wales many landslides tend to occur at or below horizons of seatearth, such as that below the No. 2 Rhondda, partly by reason of the associated ground-water and lines of springs (pp. 173–175, 186–187, 272) and partly because of the clayey nature of many seatearths after weathering (pp. 175, 270–272, 280–282).

(iv) Recognition that the most generally effective measure for remedying landslides is adequate drainage of the seat of the slide (pp. 175, 201, 216–217, 234–244, 258, 275, 277, 283 and 285–286).

(v) Recognition of the importance to the overall stability of a colliery tip of the stability of its toe (pp. 181, 188).

(vi) Recognition of the danger of cutting away the toe of a tip or a slide, or or making a cutting into a marginally stable slope (pp. 172, 188, 228–229, 236 and 274).

(vii) Recognition that in South Wales landslides are frequently heralded by slow movements which may continue for long periods (pp. 183, 192, 197 and 258–259). These movements are likely to pass undetected unless some structure is involved (p. 183) or unless a line of pegs is put in to indicate it (pp. 258–259).

(viii) Recognition, by Mr G.S. Morgan at least, that the addition of weight at the top of an already unstable mass would accelerate its sliding movements (p. 235).

8 *Instances of possible flow-slides in tip material*

Although the term 'flow-slide' is not used in the paper or the discussion, the descriptions and sketches given suggest that the following failures may have come into this category:

(i) The Pentre, pre-1916 alide (pp. 218–219). The description is not clear, but from the sketch cross-section (Fig. 41, p. 219) and the fact that a boy was killed by the failure, it is possible that this involved a flow-slide of the tip material.

(ii) The Pentre, 1916 slide (pp. 211–218). The description does not suggest a flow-slide, but the cross-section (Fig. 37, p. 214) is such as to warrant a further investigation of this case. This slide led to a costly lawsuit which may yield further information.

(iii) The Pochin slide (no date given) (pp. 240, 260–264). A large quantity of colliery refuse is described as being carried for a distance of 300 yards down a slope of 9° (1 in 6·4), the cross-section (Fig. 48A, p. 263) is also strongly suggestive of a flow-slide, which appears to have involved a school situated on the valley floor.

(iv) The Mardy slides (p. 245). Two serious tip slides at Mardy are briefly mentioned by Captain T.E. Richards. Both slides filled the valley and dammed the stream and should be checked upon as possible flow-slides.

C *Instances of movements in old disused tips*

(i) The Blaina slide (pp. 209–211). This slide involved a grass-covered tip of colliery waste from workings in the Tillery Vein. From the cross-section (Fig. 35, p. 210) the tip appears to have failed by retrogressive rotational slipping. The toe of the tip was moved a distance of the order of 100 ft.

(ii) The Pentre, 1916 slide (p. 211). The description of the placing of the upper tip suggests that, on weathering, the toe of the tip moved outwards, resulting in a lower average slope.

D *Procedure as to choice of new tipping sites*

(i) Evidence that, in some cases, engineering advice was called for on suitability of proposed tipping sites. Mr G.S. Morgan mentions (pp. 234) that he was asked about tipping on a valley side in the Rhondda Valley. He advised against it: his advice was neglected and trouble arose. Mr Morgan also warned against tipping up the side of the valley at Cwm tip, Ebbw Vale (pp. 236–237).

(ii) Evidence that the importance of drainage of the ground before tipping was recognised.

At the Cwm tip, Ebbw Vale (pp. 236–237), Mr G.S. Morgan drew attention to the fact that tipping had begun up the hillside, upon ground which had not been prepared by drainage works. He warned that a continuation of this tipping, without adequate drainage, 'would start a huge slide that would probably overwhelm the valley'.

Mr R. James also emphasised (p. 284), in principle, 'the absolute necessity of the preliminary drainage of all ground selected for tipping'.

(iii) Evidence that the need for careful examination of proposed tipping sites by qualified experts was recognised.

Mr R. Richards hoped that (p. 272) as a result of Professor Knox's work, 'mining engineers would make a more careful investigation of so-called suitable ground for colliery tips'.

Mr H.L. Porcher remarked that (pp. 276–277) 'one great lesson to be learnt from Professor Knox's paper was that no new colliery township should be established in any area until men of eminence in scientific circles . . . had surveyed the area in order to foretell what was likely to happen, and until the necessary remedial measures had been taken to avoid landslides'.

Professor Knox, in concluding, suggested the setting up of a 'Remedial Works Board' for dealing with landslides in South Wales, stating that (pp. 266–267) 'it is surely better to try and evolve some positive system of dealing with these disastrous phenomena than to regard them as necessary evils for which no one is responsible'.

Press report of Abercynon slip

Western Mail, 6th December 1939

LANDSLIDE OF 500,000 TONS OF DEBRIS

Road buried to depth of 20 ft

An enormous quantity of debris estimated as amounting to anything up to half a million tons, swept down from the Abercynon Colliery tip overlooking the Cardiff, Merthyr and Aberdare main road between Cilfynydd and Abercynon at 1.45 on Tuesday afternoon.

The fall completely blocked the road to a depth of 20 to 25 ft for a distance of about 150 yards.

About half a dozen men were picking coal from the tip at the time, but they were not involved in the slide, which provided a terrifying spectacle.

Suddenly they heard a rumble and then saw part of the tip move. It swept down the steep mountainside at a terrific speed until it reached the road, when there was a tremendous crash as it struck the telegraph posts and wires and broke them down. The avalanche was between 100 and 150 yards wide, and in depth was of the size of an average house.

Motorist's escape

One of the coal pickers, Thomas Iorwerth, of Cwm Cottages, Cilfynydd, told a *Western Mail* reporter that after they heard the first warning rumble the whole huge mass was down on the road within three minutes.

The coal pickers witnessed the narrow escape of a motorist who was approaching the scene from the direction of Abercynon. He saw the avalanche coming down, stopped and reversed quickly, and got clear.

There is extremely heavy traffic of motor-buses, lorries, cars, cycles and pedestrians on the road, and it could well have been that several vehicles and pedestrians might have been buried beneath the avalanche without hope of being extricated alive.

The motorist who escaped stated that the road in front of him was clear of all traffic so it was immediately made clear that there was no one under the avalanche.

Some of the coal pickers had been in the habit of picking coal on that part of the tip where the landslide took place, but an ominous move of the tip was observed on Monday and Mr. Iorwerth and his fellow coal pickers were warned not to work on that part of the tip.

At the time of the landslide they were working on the extreme side of the tip nearest Cilfynydd and about 50 yards away from the landslide.

Colossal task

The Chief Constable of Glamorgan, Mr. Joseph Jones, Superintendent William Macdonald, Superintendent Tom Davies, Inspector Wilkins, Sergeant Carter and Police Constable Vaughan hurried to the scene and were kept busy diverting traffic and keeping sightseers from Cilfynydd and Abercynon away from the danger spots.

Engineers and a large party of workmen of the Powell Duffryn Associated Collieries Ltd were hurried to the scene to begin the colossal task of clearing the roads. They had petrol navvies working at each end.

In addition to blocking the road the landslide blocked the adjoining canal and diverted the course of the River Taff for 200 yards to flood the neighbouring fields.

The Pontypridd and Nelson railway, now used only for the conveyance of colliery materials between Abercynon and Albion Colliery, Cilfynydd, was also blocked.

APPENDIX 3

Details of soil tests, piezometer readings, etc.

A PRELIMINARY INVESTIGATION INTO CERTAIN MINERALOGICAL AND CHEMICAL ASPECTS OF TIP 7 OF MERTHYR VALE COLLIERY AT ABERFAN

A Weeks of the Building Research Station

Summary

Ten samples taken at 10 ft intervals through Tip 7 of Merthyr Vale Colliery have been examined for any possible chemical or mineralogical variations.

The mineral assemblage of all samples consisted of kaolin, illite, quartz, calcite and pyrites; although some differences in their relative proportions were observed, these were not considered to be significant.

Systematic variations in the content of water-soluble Na^+ and SO_4'' were detected, but in the absence of comparable values from a stable coal-shale tip, these were considered to be entirely consistent with the environment of the material.

It is suggested that, while the plastic and potential flow properties of coal-shale mixtures are more probably influenced by water-content and pore-size distribution, factors such as particle size and orientation relationships will also be of some significance, and further work will proceed in this direction.

Introduction

Consequent upon the sudden collapse at the end of 1966 of one of the tips of waste materials from Merthyr Vale Colliery, a preliminary investigation has been made to determine whether any detectable mineralogical or physico-chemical changes could have influenced the flow properties or affected the stability of a section of this tip.

The tip under investigation was Tip 7, situated at Aberfan, and this consisted largely of washery shale, run-of-mine rubbish and screen belt pickings. This mixture of shale and coal discard had accumulated since April 1958 until tipping ceased in October 1966, and the rate of tipping is estimated to have been in excess of 50,000 tons per annum.

Also deposited on the tip were the tailings from the filtration plant, and particular interest was given to the fact that a flocculating agent, known commercially as 'Dryfloc', had been added to the tailings stream, and would also have been deposited on the tip. Since its composition was known to have been 52% starch, 43% $CaCl_2$, 4% $ZnSO_4$, 1% formaldehyde, consideration was given to the possibility of determining any residual traces of this agent which might have influenced the properties of the particles in the tip material.

Description of samples

The samples received had been taken every 5 ft from a borehole which had been put down through Tip 7 and which were numbered T7/1 (5 ft), T7/1 (10 ft), T7/1 (15 ft), etc, down to T7/1 (100 ft), the last representing the base of the tip.

The samples examined were selected from this sequence, and represented 10 ft intervals, and hence were those numbered T7/1 (10 ft), T7/1 (20 ft), etc, down to T7/1 (100 ft).

The appearance of the samples was that of a mixture of shale, clay and fine coal. No obvious differences such as colour, texture or hardness were noticed, except in the case of sample No. T7/1 (90 ft) which was comparatively friable, and which could easily be crumbled in the hand.

Preparation of samples

Mechanical analysis. The samples consisted of shale and fine coal, and since particle-size distribution curves were to be obtained in the Geotechnics Division, it was decided to separate the coal from the shale by density differentiation. Since the density of shale is approximately 2·6, compared with 1·6 for coal, it was concluded that a satisfactory separation could be made by using a liquid of density of about 2·0. Accordingly an appropriate mixture of bromoform and 'Inhibisol' was made, of relative densities of 2·8 and 1·3 respectively. A large glass vessel was fitted with a drain spout at the bottom, to which was attached a length of clear plastic tubing closed with a screw clip. The vessel was filled with the Inhibisol-bromoform mixture, and the sample was poured in a little at a time; after standing for about an hour, a clean separation into two fractions was obtained. When all of the sample had been added, the heavier fraction was drained off, and the lighter fraction washed out of the vessel. Both fractions were then dried at 60°C.

Mineralogical and chemical analyses. A portion of each sample was taken in the 'as received' condition, and was as representative as possible, and was ground in an agate mortar to pass a No. 100 B.S. sieve. Half of this was retained for the chemical analysis of the water-soluble ions, and the remainder was ground further to pass a No. 300 B.S. sieve for the X-ray diffraction examination. A separate X-ray examination was made for the non-clay and clay minerals present in each sample. For the non-clay minerals, a photographic method for recording the characteristic X-ray diffraction patterns was used, with the aid of a Guinier-type focusing camera and CuKα radiation. For the clay minerals, some of the material passing the 300 B.S. sieve was dispersed in distilled water, using a complex sodium phosphate ('Calgon') and violent agitation with a mechanical stirrer producing as much turbulence as possible. This suspension was allowed to stand in a tall glass cylinder, and the $<2\mu$ fraction siphoned off from the level calculated from Stoke's Law. This fraction was saturated with Mg^{++}, and the now flocculated suspension was deposited on to a porous ceramic plate under suction. A specimen of highly oriented clay minerals was produced in this way, and their characteristic interplanar basal spacings were determined with a recording diffractometer.

Results

Mechanical analysis. Particle size distribution curves obtained in the Geotechnics Division showed no significant differences between the samples, nor between the two fractions of each sample obtained by density separation. No apparent inter- or infra-sample variations were thus observed, but these results will be available in greater detail elsewhere.

Mineralogical analysis. The $<2\mu$ fraction of all samples contained the clay minerals illite and kaolin, together with quartz. No significant differences in the relative proportions of these phases could be detected and no expanding-lattice mineral was observed. The crystalline phases detected in the samples as a whole are tabulated below, together with an indication of their relative proportions.

Sample depth	Minerals detected				
	Kaolin	Illite	Quartz	Calcite	Pyrites
10 ft	xxx	xxx	xxx	x	xx
20 ft	xxx	xxx	xxx	x	x
30 ft	xxx	xxx	xxx	xx	x
40 ft	xxx	xxx	xxx	xx	x
50 ft	xxx	xxx	xxx	x	x
60 ft	xxx	xxx	xxx	x	x
70 ft	xxx	xxx	xxx	x	x
80 ft	xxx	xxx	xxx	x	xx
90 ft	xxx	xxx	xxx	x	x
100 ft	xxx	xxx	xxx	x	x

xxx = present in large amounts
xx = present in small amounts
x = just detectable.

Chemical analysis. The water extract obtained at pH = 7·0 was analysed for Na^+, Mg^{++}, K^+, Ca^{++}, Cl' and SO_4''. The only systematic variations observed were in the values for Na^+ and SO_4'', but all the results are tabulated below, together with the weight of the water soluble solids dried at 105°C, expressed as a percentage of the weight of the dried sample.

Sample depth (ft)	Total extract (%)	Ions analysed					
		SO_4''	Cl'	Ca''	Na^+	K^+	Mg^{++}
10	0·18	0·05	<0·001	0·02	<0·01	0·02	0·002
20	0·14	0·04	<0·001	0·01	0·02	0·03	0·001
30	0·27	0·09	<0·001	0·02	0·09	0·03	0·003
40	0·34	0·11	<0·001	0·02	0·08	0·04	0·004
50	0·29	0·12	<0·001	0·02	0·14	0·03	0·003
60	0·29	0·12	<0·001	0·01	0·14	0·03	0·003
70	0·25	0·10	<0·001	0·01	0·14	0·02	0·002
80	0·61	0·35	<0·001	0·04	0·21	0·04	0·009
90	0·83	0·46	0·002	0·03	0·34	0·02	0·014
100	0·24	0·13	<0·001	<0·01	0·13	0·02	0·004

Discussion

From the mechanical analyses obtained, it would appear that no significant differences in particle size distribution were observed. It had been thought probable that, since the drainage trench cut along the base of the tips in 1965 had become partially blocked, considerable quantities of fine material might have been washed away from the tip. However, there was no evidence that the tip material contained an abnormally low content of fines nor, since the particle size distribution between the shale and coal fractions exhibited no significant differences, was there any evidence of selective leaching based upon density differential.

X-ray diffraction analyses showed that the minerals present were those common in Coal Measure deposits; no unusual crystalline phases were detected, nor were any clay minerals possessing an expandable lattice. Of the minerals which were detected, considerable variations in relative proportions were observed, but these were not considered to be significant.

The chemical analyses of the water extracts were of some interest, although rather complex. There appeared to be little systematic variation with depth, except for Na^- and SO_4'' which, as can be seen from the above table, increased noticeably in concentration until the 90 ft level. This was rather unexpected, but is probably not significant, since the long-term leaching effect of rain and general precipitation would tend to concentrate the soluble ions towards the base of the tip. The comparatively high concentration in the 90 ft sample would, therefore, be simply explained, but the sudden reduction in the 100 ft sample requires additional comment. Since the concentration of Na^+ and SO_4'' in this sample was approximately one-third of the sample only a few feet above, it was assumed that considerable leaching out must have taken place at this level, and since this represented the base of the tip, the leaching could only have been due to rising ground-water and surface run-off from the slopes on which the tip was built, together with the effect of any possible stream or natural springs which might underlie it. This variation in concentration was not exhibited by the other ions, and the reason for this cannot as yet be explained. However, much of the interest in the chemical analysis was in the possibility of detecting any residual traces of the flocculating agent 'Dryfloc'. Since the major inorganic constituent of this additive was $CaCl_2$ and since the concentration of neither Ca^{--} nor Cl' exhibited any systematic variation through the vertical section of the tip, it was concluded that should there be any change in surface properties of the particles of the tip material at various depths, these would not have resulted from an irregular concentration of this agent through the tip; indeed, there was no evidence to suggest that any traces of this additive remained.

Conclusions

One of the main purposes of this preliminary investigation was to determine whether the stability of any section of Tip 7 could have been influenced by any possible mineralogical or chemical changes in the constituent particles.

While some variations in the mineralogy of samples taken from various depths in the tip were seen, these were not considered to be significant, and certainly no clay mineral possessing an expandable crystal lattice was detected.

Considerable variations in the chemical analyses were obtained, but with the exception of the Na^- and SO_4'' contents, no systematic variations were seen. The increasing concentration of Na^+ and SO_4'' with depth of sample is interesting, but would appear to be consistent with the natural conditions obtaining in the tip, and in the absence of analogous analyses from a stable tip, were not considered to be particularly significant. No evidence was seen of residual traces of the flocculating agent 'Dryfloc' in the tip material.

It did not appear, therefore, that the variations in the mineralogical and chemical analyses of the samples taken from successive depths of the tip would have affected the stability of either the tip as a whole, or any section of it. The plastic and potential flow properties of the tip material are more probably influenced by other factors, and work is proceeding in an investigation of particle size and orientation relationships.

Consolidated Drained Triaxial Tests

Test number	Material	Water content % dry wt.	γ lb/ft³	γ_D lb/ft³	Approx. depth below natural ground (ft)	Sample size	σ_3 lb/in.²	$(\sigma_1-\sigma_3)_f$ lb/in.²	$\delta V/V_{max}$ %	$\delta V/V_f$ %	Φ'	Mechanical analysis % by wt. of particle size				L.L. %	P.L. %	Testing laboratory
												<2 mm	2–0·06	0·06–0·002	<0·002			
1TP	Drift	17·0	129		3·50	U1½	10	20·9	0·43	0·43	37°							B.R.S.
2TP	Drift	16·8	118		3·75	U1½	100	307	3·45	3·46								
3TP	Drift	15·4	133		4·08	U1½	50	150	0·96	−0·95		29	45	20	6			B.R.S.
4TP	Drift	21·0	125		4·67	U1½	50	140	−3·80	−3·74								B.R.S.
A1-6	Drift	11·8	134		7·5	U4	40	134	−0·65	−0·40	37°	43·5	34·5	16·0	6·0	22·8	14·3	B.R.S.
A1-11	Drift	13·0	131		11·15	U4	20	54·3	−0·85	−0·78		31·0	33·0	27·0	9·0	26·7	15·0	B.R.S.
A1-12	Drift	13·8	140		13·0	U4	10	31·6	−0·38	−0·17		35·0	27·0	25·5	12·5	26·9	15·2	B.R.S.
K5-2	Drift	13·0			4·5	U4	10	30·4	−0·9	−0·96	38½°	43	38	15·5	3·5			B.R.S.
K3-7	Drift	10·4			16·5	U4	20	71·9	−0·3	−0·14		38	21	31	10			B.R.S.
K9-3	Drift	13·2			4·0	U4	10	38·4	−0·24	+0·10		24·5	36·5	28	11	24·2	15·3	B.R.S.
K4-3	Drift				4·0	U4	30	103·1	−1·45	−1·40		35	33	22	10			B.R.S.
Z2-5-1	Drift	21·0	123		1·25	U4 U1½	20	55·5	−2·53	−2·53	35½°		68	22	10	22·1	17·2	I.C.
2	Drift		122			U1½	10	28·4	−1·95	−1·95								I.C.
Z2-6-1	Drift	21·0	128		2·75	U4 U1½	40	144·1	−2·96	−2·96	40°					22·1		I.C.
2	Drift		125			U1½	30	100·1	−2·70	−2·70								I.C.
Z2-8-1	Drift	10·1 to 11·8	145		6·0	U4 U1½	10	30·5	−0·85	−0·75	36°	30	36 51	22 32	12 17	19·7	12·9	I.C.
2	Drift		142			U1½	20	55·6	−1·26	−1·05								I.C.
3	Drift		143			U1½	30	84·7	−1·22	−1·00								I.C.
4	Drift		143			U1½	40	112·4	−1·41	−1·25								I.C.

[For material passing No. 7 sieve]

B3-2-1	Drift	14·9	139		2·0	U4 U1½	10	28·5	+0·6	+0·20	32°	6	43	26	25	23·3	14·7	I.C.
2	Drift		140			U1½	25	62·3	−1·12	−0·96								I.C.
3	Drift		137			U1½	40	93·2	−1·50	−1·20								I.C.
B3-2	Drift	23·5				T	20	43·5			31½°							I.C.
B2-5-1	Drift	12·4	141		15·5	U4 U1½	25	51·2	−0·72	−0·45	29°	6	43	26	25	22·7	15·3	I.C.
2	Drift		139			U1½	10	20·6	+0·90	+0·40								I.C.
3	Drift		141			U1½	40	75·1	−1·22	−1·05								I.C.
T-C5-1	Tailings from east ridge of Tip 7	24·0				1½R	25	57·0	−2·16	−1·90	32½°							I.C.
2						1½R	40	95·8	−3·25	−3·25								I.C.
3						1½R	10	27·3	−1·80	−1·70								I.C.
T-CP-1		23·1				1½R	25	63·0	−2·45	−2·20	33½°		47	31	22	26·5	19·0	I.C.
2		23·1				1½R	40	100·6	−2·70	−2·55								I.C.
3		23·0				1½R	10	26·8	−2·00	−1·90								I.C.
T-T		25·5				T	20	44·5										I.C.
KT2	Tailings from screens	23·8					20	46·5			33½°		21	54	25			I.C.
A-T-1 to 4											31½°							K.C.
G53	Crushed shale					T	20	52·0			35°							I.C.
G54	Crushed shale $<2\mu$					T	20	32·6			26·7°					28·4	24·0	I.C.

Note: Samples size T denotes special test using thin layer of material inclined at 45° + Φ′/2 on the surface of cut porous stones.
Samples T-CP had plane cut through them before test.

Consolidated Drained Triaxial Tests

Test number	Material	Water content % dry wt.	γ lb/ft^3	γ_D lb/ft^3	Approx. depth below natural ground (ft)	Sample size	σ_3 lb/in.^{2}	$(\sigma_1-\sigma_3)_f$ lb/in.^{2}	$\delta V/V_{max}$ %	$\delta V/V_f$ %	ϕ'	Mechanical analysis % by wt. of particle size				L.L. %	P.L. %	Testing laboratory
												2 mm	2–0·06	0·06–0·002	0·002			
13	Slip-plane sample tubes were driven through the slip plane so that it lay approx. normal to axis of each	9·1	110			U1½	10	27·3	1·56	0·98	35·3°	16	34	27	23			B.R.S.
18		14·1	114			U1½	30	51·0	2·88	1·80	27·3°							B.R.S.
22						U1½	80	102·3	−1·45	−1·45	23·0°					25·3	15·5	B.R.S.
24		14·4	124			U1½	110	(111*)			(19·5°)							B.R.S.
26		16·3	128			U1½	44	55·6	−1·01	−1·01	22·8°					25·1	15·4	B.R.S.
27			122			U1½	80	87·6	−1·72	−1·64	20·7°					26·5	16·0	B.R.S.
2	Slip-plane tube driven so that plane inclined in sample	12·7				U1½	20	18·8	−0·56	−0·56	18·5°							I.C.
FS-1	Slip-plane shear					T	20	17·2			17·5°		34·5	30·5	35·0	31	15	I.C. and B.R.S.
	1 in. above slip-plane											25	26·5	22·5	26·0			B.R.S.
	2 in. above slip-plane											26	24	24	26			B.R.S.
	3 in. above slip-plane											13	31	28·5	27·5			B.R.S.
TIP-B-1	Tip 7 material from bulk sample taken just above culvert, passing $\frac{3}{16}$ in. sieve	7·21	95			1½R	10	32·0	+1·00	+0·60	33½°							I.C.
2		7·18	97			1½R	25	63·8	−4·70	−4·70								I.C.
3		7·02	101			1½R	30	72·2	−6·50	−6·50		40	52	2	6			I.C.
4		7·00	100			1½R	40	97·0	−7·90	−7·90								I.C.
5		7·45	100			1½R	40	102·0	−9·10	−8·80								I.C.

* Sample only strained to 8% at time of writing: probably not quite reached failure.

T7/1-10′	Tip 7 material	7·9	100	93	10	U4	10	31·9	−4·8	−4·8	39½°						U.C.S.
15		10·5	100	90	15	U4	15	43	−5·3	−5·3							
20		11·8	117	105	20	U4	20	76	−3·3	−3·3							
25		12·0	116	103	25	U4	5	23·4	−0·7	−0·7							
35		12·0	110		35	U4	10	36·2	−1·4	−1·4							
40		12·0	119		40	U4	20	66	−4·4	−4·4		68	24	8			
45		6·0	115	109	45	U4	25	80·5	−3·1	−3·1							
50		5·4	126	119	50	U4	20	72	−1·8	−1·8							
55		9·7	109	100	55	U4	30	82	−2·7	−2·7							
65		6·0	129	121	65	U4	35	105	−2·8	−2·8							
100		6·4	125	118	100	U4	25	87	−3·2	−3·2							
110		6·4	118		110	U4	15	62	−1·3	−1·3							
Z2-2	Tip 4 material	11·0		105	4	U4	9·9	39·0	−0·50		37·7°						I.C.
Z2-3		10·5		112	6	U4	41·7	130·1	−0·12								
Z2-4		20·3		93	8	U4	19·9	62·8	−0·36								

Constant head permeability tests made in a 4 in. dia. oedometer

Material	Permeability cm/sec
Tip 7 material Head just below ground level	$6{\cdot}6 \times 10^{-3}$ $4{\cdot}14 \times 10^{-8}$
Material just above slip plane	$1{\cdot}82 \times 10^{-9}$

Consolidated undrained Triaxial Tests

Test number	Material	σ_{3f} lb/in.²	$(\sigma_1 - \sigma_3)_f$ lb/in.²	A_f	Water content % dry wt.	γ lb/ft³	Φ	Sample size	Depth (ft)	Consol pressure lb in.²	Testing laboratory
T7/2-11′	Tip 7 material	3·8	16·0	0·388			41½	U4	11	10·0	U.C.S.
27		8·9	36·0	0·287	27·0	90		U4	27	19·2	U.C.S.
35		9·5	33·5	0·544	9·0	128		U4	35	27·7	U.C.S.
43		15·7	53·7	0·412	7·7	116		U4	43	37·8	U.C.S.
51		7·5	30	0·26	6·1	134		U4	51	15·3	U.C.S.
A-T-1 to 4	Tailing from screens						30				K.C.

Bulk samples taken from " Mud Run " which occurred on 30th November, '66

Sample number	Bulk water content	Matrix water content	ρ	γ lb/ft³	γ_D lb/ft³	L.L.	P.L.	% passing No. 36 sieve	Mechanical analysis			Testing laboratory
									>2 mm	2–0·06	<0·06	
A6	11·5	18·3	1·97	111·5	100·0	29	21	17	73	15	12	U.C.S.
A7	17·6	28·0	2·14	114·0	97·0	29	20	37	51	25	24	U.C.S.
A8	17·4	29·1	2·12	113·0	96·7	29	23	37	48	27	25	U.C.S.
A9	16·1	22·2	2·09	113·4	97·7	28	24	32	52	28	20	U.C.S.
A10	16·4	23·9	2·13	114·4	98·3	31	21	34	52	26	22	U.C.S.
A11	12·5	21·7	2·16	119·4	106·1	27	22	17	62	30	8	U.C.S.
A12	11·9	17·8	2·07	115·8	103·5	27	21	18	68	20	12	U.C.S.
A13	12·2	21·1	2·16	119·8	107·0	28	22	21	63	23	14	U.C.S.
A14	10·8	16·0	2·42	133·0	120·0	27	19	15	73	17	10	U.C.S.

Results of Field Tests

Sand Replacement Density Measurements

Date	Bulk density lb/ft³	Dry density lb/ft³	Water content %	Position
5–1–67	102	93·6	9·0	Between T7/1 and T7/2 at 944 O.D.
10–1–67	118	107·8	9·6	Near T7/1 at 993·5 O.D.
13–1–67	104	95·9	8·7	Between T7/1 and T7/2 at 983 O.D.
1–3–67	117	107·2	9·0	Near F5 at 541 O.D.
2–3–67	126	115·6	9·0	

Falling Head Permeability Tests

Date	Piezo-meter number	Depth of tip (ft)	Depth of tip (O.D.)	k cm/sec
15–2–67	K1	7·0	788·0	9·5 · 10^{-6}
15–2–67	K2	15·0	779·6	1·1 · 10^{-5}
15–2–67	K3	33·0	773·3	4·1 · 10^{-6}
15–2–67	K4	23·5	784·0	2·7 · 10^{-5}
15–2–67	K9	9·5	1020·5	3·2 · 10^{-5}
15–2–67	K10	19·0	1012·1	4·5 · 10^{-6}
15–2–67	E4	51·0	542·4	4·5 · 10^{-5}

Borehole No. T7/1 (depth in feet)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110
Bulk density from wt. of U4 sample (lb/ft³)	111	82	97	90	108	97	104	114	116	124	109	111	111	129	125	111	113	109	106	111	111	107
Standard penetration number	3	6	36	16	17	15	30	15	26	23	22	21	35	33	34		44	45	44	46	50	

Borehole No. T7/2 (depth in feet)	3	11	19	27	35	43	51	59	67	75	83	91	101·5
Bulk density from wt. of U4 sample (lb/ft³)	92	73	90	92	120	117	133	130	117	94	138	115	124
Temperature (°C)	14	22	28	32	38	38	38	38	38	38	33	31	30

Rainfall Measured at Mountain Ash

February–March 1967	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	1	2	3	4	5	6
Daily rainfall (in.)	·20	·09	Tr				Tr			Tr				·03	·39	·91	·02	1·02	·46	1·04	·19	1·35	·02	·07	·59	·01	3·46	·14	·04			·01	·03	·06

	C4	D4	E4	F3	F6	HG1	HG2	HG/5M3	K1	K2	K3	K4	K5	K7	K8	K9	K10	K11	K12	K14
Surface level	686·0	647·2	593·4	553·7	533·6	733·2′	920·9′	839·0′	795·0′	794·6′	806·3′	807·5′	868·8′	878·5′	880·7′	1030·0′	1031·1′	1064·6′	1064·5′	553·0′
Natural ground level																				
Date																				
23 11 66		622·4																		
27		622·4																		
6 12 66			588·1																	
7			589·7											Dry						
8			590·6											Dry						
9			591·0			696·0								Dry						
10			591·3			699·2								Dry						
12			592·2			699·7								Dry						
13			592·3			699·7								Dry						
14			592·6			699·7								Dry						
15			592·7			699·7								Dry						
21 12 66			593·4			699·5								Dry						
3 1 67			594·2	535·4	522·1	707·2								Dry						
5			594·2	534·6	522·0	703·9				784·2	778·5			Dry	Dry					
7			594·0	534·3	521·9	700·2				784·4	778·6			Dry	Dry					
9			Frozen	534·3	521·4	699·5			790·4	783·8	778·3	784·1		Dry	Dry					
11			592·6	531·5	520·9	699·2			790·2	784·2	778·4	784·2		Dry	Dry					
17			588·6	530·2	520·9	698·6			790·0	783·3	778·3	784·4	Dry	Dry	Dry					
21			586·2	531·3	521·1	698·2			790·2	784·2	778·6	784·4	Dry	Dry	Dry	1024·7	1014·2			
28			591·6	533·8	521·7								Dry	Dry	Dry	1024·3	1013·7	1059·6	1053·6	
30			592·8	533·7	521·7				791·1	784·0	778·3	793·0	Dry	Dry	Dry	1024·2	1013·6	1059·2	1053·3	546·7
31 1-67			593·4	533·7	521·6								Dry	Dry	Dry	1024·2	1013·6	1059·1	1053·3	546·3
1 2 67	669·8		593·4	533·6	521·6				791·0	783·7	778·3	793·0	Dry	Dry	Dry	1024·3	1013·5	1059·2	1053·4	546·1
2	668·9		594·2	533·5	521·6	700·3			790·9	783·8	778·6	793·0	Dry	Dry	Dry	1024·2	1013·5	1059·2	1053·3	545·8
7	665·4		592·9	532·7	521·8	700·0	792·1		790·9	783·8	778·6	793·0	Dry	Dry	Dry	1021·6	1013·5	1059·2	1053·4	545·0
9	660·4		592·3	531·2	521·2	699·7	791·0	792·1	790·5	784·0	778·4	793·1	Dry	Dry	Dry	1022·5	1013·2	1059·2	1053·4	544·9
10	656·7		591·9	531·1	521·1	699·7	791·0	789·3	790·5	784·0	778·5	793·1	Dry	Dry	Dry	1023·1	1013·2	1059·1	1053·1	544·8
11	652·3		589·6	530·8	521·2	698·7	790·4	788·6	790·4	784·0	778·6	793·1	Dry	Dry	Dry	1022·7	1013·2	1059·0	1053·1	544·7
12	647·0		589·1	530·5	521·0	698·2	789·2	788·4	790·3	784·0	778·6	793·1	Dry	Dry	Dry	1022·2	1013·2	1059·0	1053·0	544·7
13	641·9		588·6	530·2	520·8	698·2	789·0	787·2	790·2	783·9	778·4	792·9	Trace	Dry	Dry	1021·8	1013·2	1059·0	1053·0	544·6
14	Dry		588·0	529·9	520·8	698·2	788·9	Dry	790·2	784·0	778·6	792·9	Trace	Dry	Dry	1024·1	1013·2	1059·0	1053·0	544·6
15	Dry		587·5	529·9	521·0	698·4	788·9	Dry	790·2	784·6	779·0	793·2	854·6	Dry	Dry	1021·0	1013·2	1059·0	1053·0	544·6
16	Dry		586·9	529·7	521·0	698·4	788·9	Dry	790·4	785·4	779·4	796·5	854·6	Dry	Dry	1021·2	1013·4	Trace	1053·0	544·7
17	Dry		585·8	530·5	521·1	698·4	794·0	Dry	791·0	784·9	779·1	795·0	854·6	Dry	Dry	1020·8	1013·3	Trace	1053·0	546·7
18	Dry		584·9	530·6	520·8	698·2	794·1	Dry	790·8	784·5	778·9	794·1	854·7	Dry	Dry	1020·8	1013·4	1059·1	1053·0	546·4
19	Dry		584·7	531·6	521·1	698·4	788·9	Dry	791·2	784·6	779·3	794·0	854·7	Dry	Dry	1021·9	1013·4	1059·2	1054·0	547·4
20	Trace		584·7	531·4	521·0	698·6	788·7	Dry	791·2	784·4	779·0	794·0	854·7	Dry	Dry	1022·5	1013·5	1059·2	1054·0	547·4
21	Dry		587·3	532·5	521·0	699·0	788·6	Dry	791·7	784·0	778·8	793·8	854·7	Dry	Dry	1022·6	1013·4	1059·2	1054·0	548·2
22	637·1		588·3	532·6	521·1	703·4	793·6	Dry	791·4	783·9	779·0	793·6	854·8	Dry	Dry	1022·3	1013·5	1059·1	1053·6	547·0
22	662·3		590·1	533·7	521·5	710·0	799·4	Dry	791·4	784·1	779·2	793·4	854·8	Dry	Dry	1027·7	1013·6	1059·2	1052·7	548·0
24	672·7		591·8	533·9	521·6	714·0	803·9	Dry	791·3	784·0	779·2	793·4	854·7	Dry	Dry	1023·1	1013·5	1059·1	1053·6	545·8
25	670·4		592·7	533·9	521·9	711·2	806·2	Dry	791·1	784·7	779·6	793·5	854·9	Dry	Dry	1022·7	1013·4	1059·1	1053·5	546·4
26	671·4	629·3	593·3	533·8	521·8	708·2	806·7	787·1	791·1	784·5	779·3	793·4	854·9	Dry	Dry	1022·6	1013·4	1059·2	1053·6	546·6
27	671·9	630·6	593·4	533·5	521·7	704·5	805·9	Dry	790·9	784·1	779·2	793·2	854·9	Dry	Dry	1022·4	1013·4	1059·1	1053·5	546·3
28 2 67	675·1	631·7	594·9	534·6	522·4	715·8	808·4	Trace	791·2	784·2	779·3	793·1	854·9	Dry	Dry	1022·5	1013·6	1059·2	1054·0	548·1
1 3 67	674·7	632·4	595·4–	534·6	522·3	721·9	813·3	Dry	791·6	784·0	779·3	793·4	854·9	Dry	Dry	1022·5	1013·6	1059·2	1053·7	547·8
2	674·5	632·9	595·4–	534·5	522·3	717·7	814·8	Dry	791·2	783·9	779·3	793·2	854·9	Dry	Dry	1022·1	1013·4	1059·2	1053·5	547·4
3	674·3	—	595·4–	534·0	522·3	711·7	814·8	Dry	791·1	783·8	781·8	793·1	854·9	Dry	Dry	1022·0	1013·4	1059·2	1053·4	546·1
4	674·0	633·4	595·4–	533·6	522·2	706·0	813·7	Dry	791·1	784·0	779·4	793·2	854·9	Dry	Dry	1021·9	1013·4	1059·2	1053·3	545·8
5	673·3	633·4	595·2	533·3	523·1	703·2	811·6	Dry	791·0	784·0	779·3	793·2	854·9	Dry	Dry	1022·0	1013·4	1059·1	1053·1	545·5
6	672·6	633·3	594·9	532·8	522·0	701·6	808·8	Dry	791·0	783·9	779·3	793·1	854·9	Dry	Dry	1022·3	1013·4	1059·1	1053·1	545·3
7	671·9	633·4	594·7	532·4	522·0	700·8	805·2	Dry	790·9	784·2	779·5	793·2	854·9	Dry	Dry	1022·7	1013·4	1059·1	1053·0	545·1
8	671·1	633·4	594·6	532·1	522·0	700·5	799·9	Dry	790·8	784·5	779·6	793·1	854·9	Dry	Dry	1022·6	1013·4	1059·0	1053·0	545·2
9-3-67	670·1	633·4	594·4	532·3	522·1	700·4	796·0	Dry	790·8	784·6	779·9	793·2	854·9	Dry	Dry	1022·8	1013·3	1059·1	1053·0	545·2

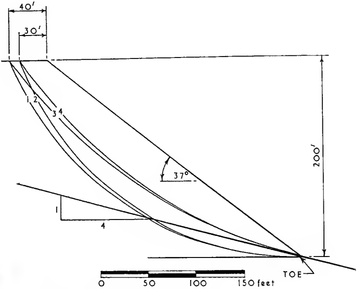
Readings (Feet O.D.)

L1	L2	L3	L7	L8	L9	L10	R2	R5	R6	R7	R8	SM1	SM2	SM3	6	8	9	14	T3/L	T7/2
994·3'	993·1'	1050·2'	1046·9	1044·6	789·1	790·0'	833·3	605·7'	1093·4	873·7	1224·1	1183·3	1183·2'	1068·5	925·8	1053·0'	1093·9'	1088·9'	979·4'	1034·0'
															891·3	1009·5'	1032·9'	1035·9'		925·0'
							Dry													
							Dry													
							Dry												Dry	Lost
							Dry												Dry	
							Dry												Dry	
							Dry												Dry	
							Dry												Dry	
							Dry												Dry	924·0
							Dry												Dry	
							Dry									1017·1	1030·2		Dry	
							Dry									1006·7	1033·3		Dry	
							Dry										1033·3		Dry	
							Dry	576·7							904·1	1005·8	1033·4	1035·9	Dry	Blocked
							Trace	572·4							904·5	1005·8	1033·5	1036·0	Dry	923·3
							Trace	567·7							904·9	1005·8	1033·5	1036·1	Dry	923·2
							765·3	563·5									1033·5	1036·2	Dry	924·2
							765·3	560·9							904·5	1006·0	1033·7	1036·2	Dry	924·2
							765·2	557·4							902·2	1006·0	1033·6	1036·2	Dry	924·8
							765·3	557·9	963·5			Dry	Dry	1056·4		1006·2	1033·9	1036·2	Dry	924·9
							765·4		988·1	747·7		Dry	Dry	1055·0	902·6	1006·2	1034·6	1036·2	Dry	924·9
							765·3			741·1		Dry	Dry	1055·0	903·1	1006·1			Dry	924·9
			Dry	Trace					984·8		1068·4	Dry	Dry	1055·0	903·5	1006·1	1033·6	1036·2	Dry	924·9
			Dry	Trace			765·4		980·4	757·6	1065·4	Dry	Dry	1055·1	904·0	1006·0	1033·6		Dry	
			Dry	Dry			765·5	571·3	974·0	755·6	1063·4	Dry	Dry	1055·0	904·0	1006·0	1033·6	1036·3	Dry	
		1007·3	Dry	Dry			765·4	571·1	966·6	757·2	1055·7	Dry	Dry	1055·1	903·9	1006·2	1033·7		Dry	924·9
		1004·6	Dry	Dry			765·6		965·8	754·5	1051·1	Dry	Dry	1055·0	903·9	1006·2	1033·7	Dry	Dry	924·9
		1003·1	Dry	Dry			765·7		968·9	753·9	1049·1	Dry	Dry	1055·0	903·9	1006·1	1033·7	Dry	Dry	924·9
		1003·1	Dry	Dry			765·6		957·3	753·5	1047·6	Dry	Dry	1054·9	903·7	1006·3	1033·7	Dry	Dry	925·0
		1003·1	Dry	Dry			765·6		955·6	753·1	1046·0	Dry	Dry	1054·9	903·5	1006·3	1033·8	Dry	Dry	925·1
		1003·2	Dry	Dry			765·6	559·6	953·9	752·8	1044·5	Dry	Dry	1054·9	903·2	1006·1	1033·8	Dry	Dry	925·0
Dry		1003·3	Dry	Dry			765·8	559·2	952·3	753·2	1042·9	Dry	Dry	1054·9	902·7	1006·3	1033·8	Dry	Dry	925·0
Dry		1003·3	Dry	Dry			765·9	558·9	950·7	752·1	1041·4	Dry	Dry	1055·2	902·4	1006·4	1033·7	Dry	Dry	925·0
Dry		1003·3	Dry	Dry			765·9	558·8	949·3	751·5	1040·5	Dry	Dry	1055·2	902·1	1006·5	1033·8	Dry	Dry	925·0
Dry		1003·6	Dry	Dry	789·4		766·0		950·5	752·1	1043·5	Dry	Dry	1055·3	902·2	1006·5	1034·0	Dry	Dry	925·8
Dry		1003·3	Dry	Dry	790·6	790·3	765·7	559·4	955·3	751·4	1051·6	Dry	Dry	1055·4	901·5	1006·6	1033·9	Dry	Dry	926·1
Dry		1003·3	Dry	Dry	791·3	790·2	765·8	560·4	966·9	751·0	1060·6	Dry	Dry	1055·5	901·5	1006·6	1034·0	Dry	Dry	926·1
Dry		1003·4	Dry	Dry	785·9	790·7	765·8	565·7	982·4	750·6	1073·4	Dry	Dry	1055·5	901·5	1006·6	1033·9	Dry	Dry	926·1
Dry		1003·5	Dry	Dry	792·6	791·0	765·7	571·7	1009·5	750·4	1026·0	Dry	Dry	1055·6	901·9	1006·7	1034·4	1036·1	Dry	926·1
Dry	859·6	1003·6	Dry	Dry	793·0	791·9	765·7	576·9	1008·5	750·9	1094·3	Dry	Dry	1055·5	902·6	1006·4	1034·2	Trace	Dry	926·2
Dry		1003·6	Dry	Dry	793·1	791·7	765·7	579·1	1013·4	751·6	1102·8	Dry	Dry	1055·3	903·2	1006·7	1035·0	1036·6	Dry	925·3
Dry		1003·6	Dry	Dry	793·1	791·9	766·1		1013·5	758·4	1094·2	Dry	Dry	1060·3	903·9	1006·6	1034·1	Dry	Dry	925·3
Dry		1003·5	Dry	Dry	793·4	792·1	766·5	578·8	998·2	755·1	1080·8	Dry	Dry	1055·2	904·5	1006·6	1034·1	Dry	Dry	925·2
Dry		1003·7	Dry	Dry	793·0	791·9	766·5	577·9	990·8	757·4	1072·9	Dry	Dry	1055·1	904·8	1006·7	1034·2	Dry	Dry	925·4
Dry	850·3	1003·7	Dry	Dry	793·1	791·9	766·3	576·5	984·1	757·1	1067·9	Dry	Dry	1055·0	905·4	1006·7	1034·1	Trace	Dry	925·5
Dry	862·5	1003·8	Dry	Dry	793·6	792·3	766·0	581·9	1020·7	757·9	1121·9	Dry	Dry	1055·4	907·2	1006·7	1035·8	1036·7	Dry	925·4
Dry	862·7	1003·8	Dry	Dry	794·1	792·4	766·3	583·1	1024·0	760·0	1108·0	Dry	Dry	1055·3	907·8	1006·8	1035·8	Dry	Dry	925·6
Dry	859·5	1003·8	Dry	Dry	793·5	Water over-flow	766·7	581·7	1004·8	763·1	1089·3	Dry	Dry	1055·2	907·7	1006·8	1035·1	Dry	Dry	925·6
Dry	855·3	1003·8	Dry	Dry	793·1	"	766·6	—	992·4	774·6	1074·8	Dry	Dry	1055·1	907·7	1006·8	1034·8	Dry	Dry	925·7
Dry	851·2	1003·8	Dry	Buried	792·8	"	766·2	577·7	982·7	765·0	1065·6	Dry	Dry	1055·1	907·7	1006·8	1034·7	Trace	Dry	925·6
Dry	847·7	1003·8	Dry		792·8		765·9	576·4	975·7		1060·9	Dry	Dry	1054·9	907·4	1006·8	1034·6	Dry	Dry	925·7
Dry	844·3	1033·9	Dry		792·7		765·7	574·6	970·7	764·6	1057·4	Dry	Dry	1054·7	906·9	1006·8	1034·6	Dry	Dry	925·7
Dry	840·7	1003·9	Dry		792·7		765·8	573·3	968·8		1054·7	Dry	Dry	1054·8	906·5	1006·8	1034·6	Dry	Dry	925·7
Dry	838·2	1003·9	Dry		792·4		765·8	571·2	963·8	764·4	1052·5	Dry	Dry	1055·0	906·0	1006·8	1034·7	Dry	Dry	925·7
Dry	835·7	1003·8	Dry		792·3		765·9	569·8	961·9	764·1	1051·4	Dry	Dry	1055·2	905·7	1006·7	1034·7	Dry	Dry	925·6

APPENDIX 4

STABILITY ANALYSES

Stability analyses of Tip 7 made at Imperial College are shown in the five drawings 1.26–1.30 inclusive.



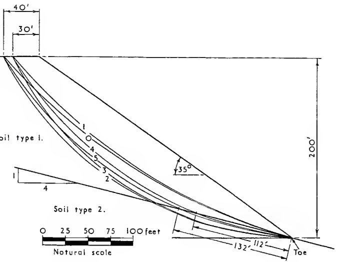
SOIL PARAMETERS :- $C' = 0$, $\phi' = 37^\circ$, $r_u = 0$ & γ IS A CONSTANT THROUGHOUT

CIRCLES 1 & 2 ARE TANGENTIAL TO A HORIZONTAL LINE THROUGH THE TOE.

CIRCLES 3 & 4 ARE TANGENTIAL TO A LINE SLOPING AT 1 IN 4 THROUGH THE TOE.

CIRCLE	SAFETY FACTOR	ϕ' REQ'D FOR F 1·0
1	1·328	29·6°
2	1·308	29·9°
3	1·162	33·0°
4	1·135	33·6°

1.26 Stability analyses of simplified sections with slope angle of 37°.



	Soil Type 1 ø′	Type 2 ø′	r_u	Circle 0	1	2	3	4	5
Group A	38°	38°	0	1·275	1·249	1·429	1·409	1·359	1·328
	38°	35°	0	1·275	1·249	1·354	1·335	1·312	1·289
	35°	38°	0	1·143	1·120	1·353	1·334	1·264	1·227
	35°	35°	0	1·143	1·120	1·281	1·263	1·215	1·190
Group B	38°	38°	0	1·275	1·249	1·442	1·421	1·365	1·332
	38°	35°	0	1·275	1·249	1·366	1·348	1·317	1·293
	38°	31°	0	1·275	1·249	1·270	1·261	1·256	1·243
	38°	28°	0	1·275	1·249	1·201	1·182	1·212	1·208
	38°	38°	0·2	1·275	1·249	1·271	1·251	1·257	1·244
	38°	35°	0·2	1·275	1·249	1·209	1·191	1·218	1·213
	38°	31°	0·2	1·275	1·249	1·132	1·114	1·168	1·173
	38°	28°	0·2	1·275	1·249	1·076	1·058	1·133	1·144
	38°	38°	0·4	1·275	1·249	1·095	1·076	1·146	1·155
	38°	35°	0·4	1·275	1·249	1·048	1·030	1·117	1·131
	38°	31°	0·4	1·275	1·249	0·989	0·972	1·079	1·101
	38°	28°	0·4	1·275	1·249	0·946	0·929	1·052	1·079
	38°	38°	0·8	1·275	1·249	0·718	0·701	0·915	0·971
	38°	35°	0·8	1·275	1·249	0·702	0·685	0·905	0·963
	38°	31°	0·8	1·275	1·249	0·681	0·664	0·892	0·952
	38°	28°	0·8	1·275	1·249	0·665	0·648	0·883	0·945
	35°	38°	0·2	1·143	1·120	1·198	1·180	1·164	1·146
	35°	35°	0·2	1·143	1·120	1·139	1·121	1·127	1·115
	35°	31°	0·2	1·143	1·120	1·064	1·047	1·079	1·077
	35°	28°	0·2	1·143	1·120	1·009	0·993	1·044	1·048
	35°	38°	0·4	1·143	1·120	1·026	1·009	1·056	1·058
	35°	35°	0·4	1·143	1·120	0·981	0·965	1·027	1·035
	35°	31°	0·4	1·143	1·120	0·924	0·908	0·991	1·006
	35°	28°	0·4	1·143	1·120	0·883	0·867	0·965	0·985
	35°	38°	0·8	1·143	1·120	0·659	0·643	0·830	0·878
	35°	35°	0·8	1·143	1·120	0·644	0·628	0·820	0·870
	35°	31°	0·8	1·143	1·120	0·624	0·608	0 808	0·860
	35°	28°	0·8	1·143	1·120	0·608	0·593	0·799	0·863

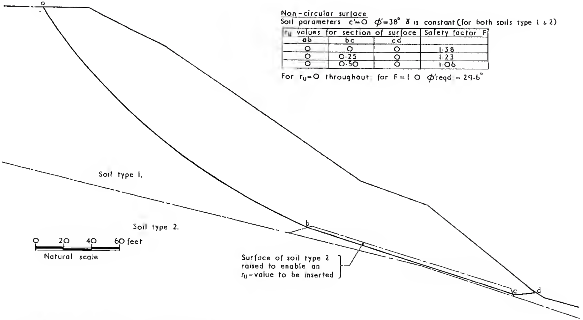
Circles 0 and 1 are tangential to a line sloping at 1 in 4 through the toe.

Circles 2 and 3 are tangential to a horizontal line through the toe.
For group A results.
for soil type 1 γ = 110 lb/cu ft
for soil type 2 γ = 110 lb/cu ft
For group B results
for soil type 1 γ = 110 lb/cu ft
for soil type 2 γ = 130 lb/cu ft

Circles 4 and 5 were chosen so that they did not pass through soils other than tip-spoil, drift or boulder clay.

STABILITY ANALYSES OF SIMPLIFIED SECTIONS

1.27 Stability analyses of simplified sections with slope angle of 35°.


o
b
c
d
Soil type 1.
Soil type 2.
0 20 40 60 feet
Natural scale
Surface of soil type 2 raised to enable an r_u-value to be inserted

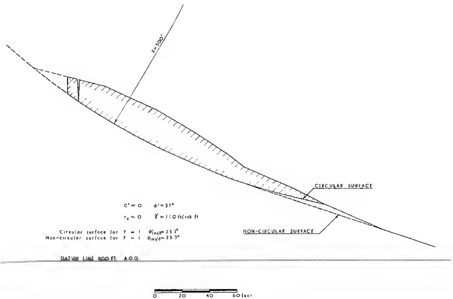
Non-circular surface

Soil parameters $c' = 0$ $\phi' = 38°$ γ is constant (for both soils type 1 & 2)

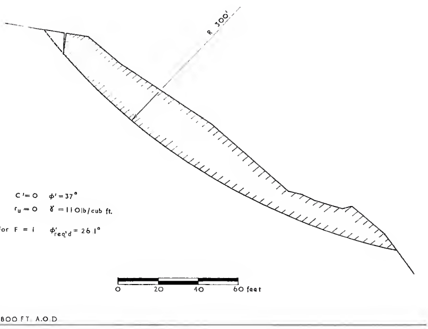
r_u values for section of surface			Safety factor F
ab	bc	cd	
0	0	0	1·38
0	0·25	0	1·23
0	0·50	0	1·06

For $r_u = 0$ throughout for $F = 1·0$ $\phi'_{reqd} = 29·6°$

1.28 Stability analysis of simplified section—non-circular slip surface


R = 500'
CIRCULAR SURFACE
NON-CIRCULAR SURFACE
c' = 0 φ' = 37°
r_u = 0 γ = 110 lb/cub ft
Circular surface for F = 1 $\phi'_{req'd}$ = 25.1°
Non-circular surface for F = 1 $\phi_{req'd}$ = 25.3°
DATUM LINE 800 FT. A.O.D.
0 20 40 60 feet

1.29 Failure surface (section Y-Y) assumed for the stability analysis of the movement in Tip 7 of February 1967.


R 300'
C' = 0   φ' = 37°
r_u = 0   γ = 110 lb/cub ft.
For F = 1   φ'$_{req'd}$ = 26·1°
0
20
40
60 feet
DATUM LINE 800 FT. A.O.D

1.30 Failure surface (section Z-Z) assumed for the stability analysis of the movement in Tip 7 of February 1967.

APPENDIX 5

MODEL TESTS

A model of the Aberfan tip complex was built to a natural scale of 1:100 at Swansea University (see Fig. 1.31). In a report prepared by Dr H.E. Evans and Professor A.H. Naylor, the scope of the work was described as:

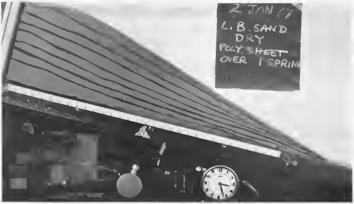
> 'The initial object was to construct a model of the Aberfan tip complex in order to demonstrate qualitatively, possible modes of failure in Tip No. 7 and the accompanying flow of tip material from the area.
>
> 'Subsequent experimentation and analysis indicates that whereas the mechanics of a tip failure may be demonstrated, the production of a material flow is difficult to reproduce on a model without scale distortion and the use of materials and fluids other than those existing at Aberfan.'

A two-dimensional model of the end of Tip 7 was built in a seepage tank at Imparial College under the direction of Professor J.R.D. Francis to demonstrate various mechanisms of failure under the action of water pressure, including the influence of a weak layer at tha base of the sliding mass.

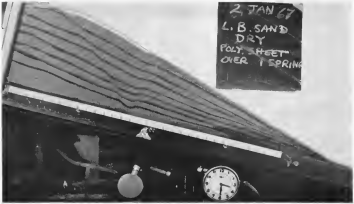
A sequence of photographs showing failure is given in Figs. 1.33–1.38 inclusive.

1.31 Model of tip complex built to natural scale of 1 to 100.

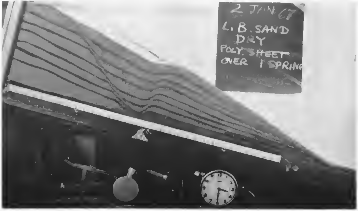
1.32 Failure of model of Tip 7.


2 JAN 67
L. B. SAND
DRY
POLY. SHEET
OVER 1 SPRING

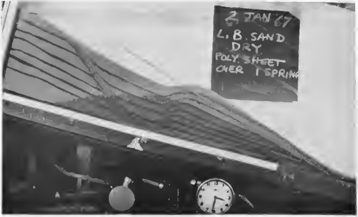
1.33


2 JAN 67
L. B. SAND
DRY
POLY. SHEET
OVER 1 SPRING

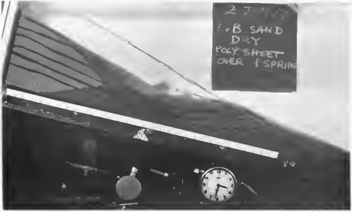
1.34


2 JAN 67
L. B. SAND
DRY
POLY. SHEET
OVER 1 SPRIN

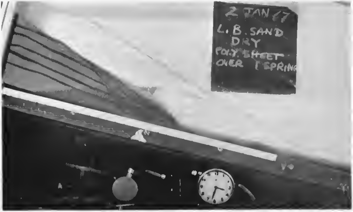
1.35


2 JAN 67
L. B. SAND
DRY
POLY. SHEET
OVER 1 SPRIN

1.36


2 J 1 77
L. B. SAND
DRY
POLY. SHEET
OVER 1 SPRING

1.37


2 JAN 77
L. B. SAND
DRY
POLY. SHEET
OVER 1 SPRING

1.38

APPENDIX 6

EVALUATION OF QUANTITIES INVOLVED IN THE HISTORY OF TIP 7

Purposes of quantity calculations

The purposes of the calculations of volume described in this appendix were:

1. To calculate the total quantity of material placed on Tip 7.
2. To establish the quantities involved and so far as is possible the nature of the disaster slip.
3. To establish the size and so far as is possible the nature of the slip in Tip 7 that took place in 1963.
4. To establish the mode of formation of the tip in the years 1963 to 1966.

Method of calculation

In order that parts of the tip of particular interest can be isolated for individual study the tip has been divided into a number of areas. The limits of these areas are shown on the drawings in this appendix (Figs. 1.39–1.42 inclusive).

Areas 1, 2, 4, 5, 13, 14, 15, 19, 20, 21 are together bounded by the edge of the breakaway in 1966 at the upper side and by the approximate limit of the tip in 1965 at the lower side. The sub-divisions between these areas run along prominent limits of minor slip surfaces and the like that existed after the disaster. These limits can be understood by comparing the drawings with the post-disaster map and photographs.

Areas 8, 18 and 9 have their downhill boundaries at the lowest points reached by material from Tip 7 in September 1963 for the first two and November 1964 for the third.

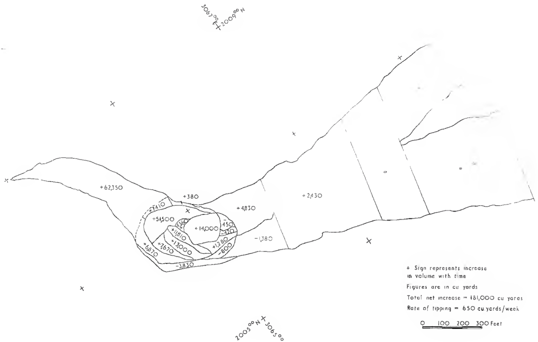
Areas 10, 11, 12 cover the area of the lower slopes of the mountain over which no material from Tip 7 had progressed until the disaster.

Areas 6, 7, 16, 17, 22 cover the remaining areas over which material placed on Tip 7 extended. The sub-divisions between areas 6 and 22 and between 7 and 22 mark the limit of the area over which tipping took place between September 1963 and June 1965.

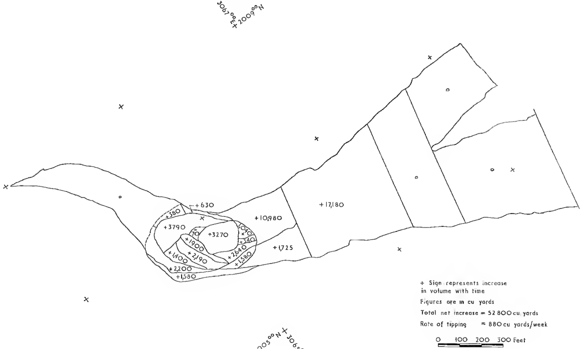
The volumes of material existing in each area at the dates of air photography (September 1963, November 1964, June 1965 and October 1966) have been calculated by Hunting Surveys Ltd, the volumes calculated are those that exist between arbitrary datum planes or, where possible, the natural ground level and the upper surface of the tip. The results of Hunting Surveys Ltd calculations are given in their statement.

Furthermore, Hunting Surveys Ltd have calculated the volumes that exist between the arbitrary datum planes mentioned above and the natural ground level. These calculations have been based on maps made from the photography of 1963, of May 1951 and also to a limited extent on the results of boreholes sunk through the tip down to the original ground, but due to the inadequacy of the photography of 1951 the results obtained are only approximate. The results of these calculations are also given in Hunting Surveys Ltd statement.

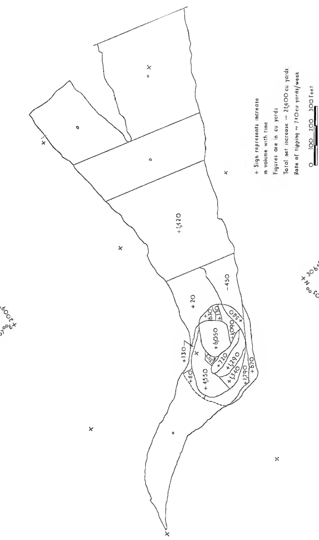
The quantity of material that passed over the canal and railway embankment and into the village has been calculated by ground measurement of marks on buildings, measurements of depth made on site and by estimates of the dimensions of the material made from photographs taken soon after the disaster and before the material had been cleared away. The figure for this quantity is approximate.



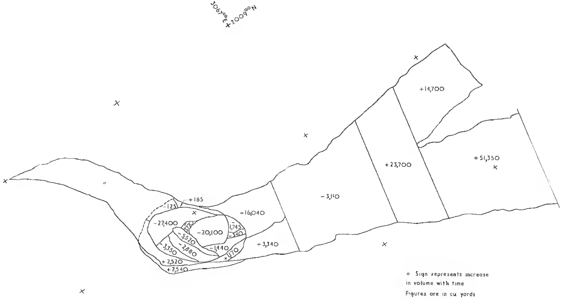
1.39 Aberfan—volumetric changes 1958–63 (281 weeks)



1.40 Aberfan—volumetric changes 1963–64 (60 weeks).



1.41 Aberfan—volumetric changes 1964–65 (29 weeks).



1.42 Aberfan—volumetric changes 1965–66 (73 weeks).

No allowance has been made for variations in volume due to expansion or contraction of material in the tip.

The figures calculated by Hunting Surveys Ltd have been used as they stand with no allowance made for any inaccuracies that may exist in these figures. Estimates of tolerances which could be quoted with the results given would be difficult to obtain and unreliable in themselves.

Results of calculations

1 The volumes of material placed on Tip 7 have been calculated to be:

Placed between 1958 and September 1963 (281 weeks)	180,000 cu yd
Placed between September 1963 and November 1964 (60 weeks)	53,000 cu yd
Placed between November 1964 and June 1965 (29 weeks)	22,000 cu yd
Placed between June 1965 and October 1966 (73 weeks)	65,000 cu yd
	320,000 cu yd

It may be noted that figures estimated by the National Coal Board in their document *History of Tipping at Mynrdd Merthyr from Merthyr Vale Colliery* give the total quantities placed in the periods February 1965 to December 1965 and January 1966 to October 1966 as 57,000 tons and 50,000 tons respectively. Using these figures to calculate the volume placed from June 1965 to October 1966 gives a figure of 65,000 cu yd assuming a density of 110 lb/cu ft, the same as calculated above.

2 The total of the volumes of material that slid on to the lower slopes of the mountain and over the railway embankment into the village is calculated to be 140,000 cu yd. This is the total of the volumes that came to rest in or lower than Area 10 on the drawing of volumetric areas. The volume that slid into the village is estimated to be 50,000 cu yd.

The volume of material that slid from the part of the tip above the spring is calculated to be 105,000 cu yd and the volume that slid from that part of the tip between the spring and the lower limit of the tip (i.e. the edge of Areas 13, 14 and 15) is calculated to be 8,000 cu yd.

An estimate of the volume of material that slipped but remained within the tip or in the areas of ground below the tip which were previously covered with tip material has been difficult to make, but this volume would appear to be about 20,000 cu yd. This can be added to the 140,000 cu yd of material which slid on to the lower slopes and into the village to give the total quantity of material involved in the slip as 160,000 cu yd.

3 The large dark-coloured mass of tip material that can be seen in the mountainside below the base of Tip 7 (Nos. 55 and 57 on Fairey Survey Ltd Report Fig. 8) is all within volumetric Area 9. The increase in the volume of material in this area between September 1963 and November 1964 was 17,200 cu yd (as compared to an increase of 1,400 cu yd between November 1964 and June 1965). At the same time the increases in the volumes of material in Areas 8 and 18, both of which lie below the bottom limit of the tip, were 11,000 cu yd and 1,700 cu yd respectively (as compared to sensibly zero increases between November 1964 and June 1965).

The total volume of material that passed the lower limit of the tip between September 1963 and November 1964 is thus almost 30,000 cu yd. The majority of this can be attributed to the flow-slide that was initiated by the slip that took place in 1963, but a small proportion will have formed part of the runs of wet material that were known to have flowed off the tip at that time.

Indication of the area of tip from which this material slipped can be inferred from the fact that whereas between November 1964 and June 1965 the increases in the volumes of material in Areas 1, 2 and 4 formed over 50% of the total quantity placed in that period, in the period during which the slip took place, September 1963 to November 1964, the increase in the same areas formed only 13% of the total placed. This is taken to verify firstly that material had left these areas between September 1963 and November 1964, and secondly that the cavity left by the slip was being filled up during the succeeding period.

4 The mode of development of Tip 7 up to September 1963 can be seen, from the point of view of the volume of slipped material on Fig. 1.39, although a wide margin of error must be assumed as the figures rely to a major extent on volumes calculated from the 1951 map (see above). The development of the tip from September 1963 to November 1964 is dominated by the slip that took place in 1963 which was dealt with in para. 4, and it has not been possible to extend the study of the development of the tip to areas unaffected by the slip.

Between November 1964 and June 1965 some indication of the mode of development of the tip can be made. It has been indicated that no material placed on the tip extended on to the 'claw' on the south-eastern side of the tip (see Hunting Surveys statement and Fig. 1.11 of this report) and it is evident the area to which the material tipped was confined to the evenly sloping area immediately below the crest (Fairey Survey report Fig. 8, No. 66).

In spite of this the increase in volume in areas outside this sloping area comprised over 50% of the total increase in volume between November 1964 and June 1965. This is consistent with the idea that during this period the tip was sliding downhill on a slip surface situated deep beneath the surface of the tip, although not all of the increase can be attributed to this cause.

An analysis by volumes of the development of the tip between June 1965 and October 1966 has been impossible to do with any accuracy. An attempt has been made to allocate the total volume tipped in the period to different parts of the tip by distributing the material in a similar way to the distribution between November 1964 and June 1965 and it is from this basis that the calculations in Section 2 of this appendix have been made.

REFERENCES

Bishop A.W., 1966. Sixth Rankine Lecture: The strength of soils as engineering materials. *Geotechnique*, Vol. 16, No. 2, p. 89–128.

Casagrande A., 1965. The role of the 'calculated risk' in earthwork and foundation engineering, Terzaghi Lecture, *Journ. Soil Mech. and Found. Eng.*, ASCE, Vol. 91, No. SM4, July 1965.

Knox G., 1927. Landslides in South Wales valleys. *Proc. S. Wales Institute Engineers*, 43 : 161–247, 257–290.

Leonards G.A. and Narain J., 1963. Flexibility of clay and cracking of earth dams, *Proc. ASCE*, Vol. 89, SM2, March, 47–98.

Pugsley Sir Alfred, 1966. The safety of structures, *Edward Arnold*, London, 156 pp.

Sinclair J., 1963. Ground movement and control at collieries, *Isaac Pitman*, London, 349 pp.

ITEM 2

Report on the stability of Aberfan Tip No. 7

J. K. T. L. NASH MA MAI (Dubl.) MICE[1]

General

1 Merthyr Vale Colliery in the centre of Aberfan lies in a valley which runs nearly N–S. The hill which flanks the valley to the west rises at an average gradient of 1 on 4½ from the town and waste from the mine has been loosely tipped on the hillside to form a tip complex containing seven distinct tips which have been numbered chronologically. The first of these, No. 1, was started before 1918 and its toe is approximately 600 yards up the hillside from the town. Above it were located all the others including No. 7 which slid with disastrous consequences on 21st October 1966 whilst still in active use.

Nature of subsoil

2 The original ground surface beneath tip No. 7 sloped at approximately 1 on 3½ and was therefore somewhat steeper than the average slope of the hillside. Since the disaster numerous borings have been carried out and these have established that beneath the ground surface there lies a layer of sandy clay soil plastered, as it were, on the valley sides. It is variable in nature and in thickness, being in places very clayey and in other places rather sandy. It contains occasional stones and much of it is typical of a glacial deposit.

Geology

3 Beneath this cover lies the massive Carboniferous Pennant sandstone which dips gently towards the Aberfan side. Some 80 ft below the base of tip No. 7 the sandstone contains a layer of coal, the Brithdir seam, which is underlain by a layer of clay with further shales and siltstones beneath it. In this area the Pennant is extremely hard and dense but the whole of it is divided into large rectangular blocks by a system of natural joints or fissures. This is a common feature in sedimentary rocks and it dominates the overall strength of the rock mass and the drainage of water through it, for these natural cracks may be several inches wide.

4 The general directions of the joints lie:
- (i) parallel to the bedding (these are generally closed);
- (ii) at 90° to the bedding and parallel to the valley;
- (iii) at 90° to these planes.

The major Kilkenny fault is in the plane of the second of these and there are other smaller faults in the same general direction.

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Drainage

5 Rainwater running down the hillside tends to collect in these fissures which run approximately along the contours. The fireclay at the seat of the Brithdir provides a barrier to the fissures and the water therefore tends to flow through the complementary fissure system and towards Aberfan due to the general dip of the rock. The discharge at the outcrop of the sandstone is, however, masked by the soil cover already referred to, and the point of emergence of the spring therefore occurs at a conveniently thin or more pervious point in the cover.

Effect of mining subsidence

6 The effect of mining subsidence in the valley bottoms both at Aberfan and in the parallel valley to the west, has been to widen long vertical fissures in this same general direction. One such fissure on the Mountain Ash side of the hilltop is several hundred feet long. In places it is 3 ft wide and clearly open to a depth of some 50 ft.

7 But mining has not been confined to the valley bottoms and the effect of working seams on wide faces from the south towards the tips (although at a depth of some 2000 ft below them) has been to cause zones of compression and tension in the rock right up to the surface. As the faces advance the pattern moves with it so that cracks opened at one stage of the operations may subsequently be closed again.

8 The effect of mining subsidence on the tip complex is twofold: first it may alter the hill gradients and second it may alter the pattern of drainage on and through the hillside by the opening or closing of fissures.

Nature of tips

9 The tipped material consists throughout of colliery waste, i.e. crushed shale from the shafts and roadways of the mine plus any shale which having been mixed with the coal has subsequently been separated from it. The grading of the material fluctuates widely but the majority would pass a 3 in. sieve and most samples would contain a small but significant clay fraction. The dominant clay minerals in this shale are kaolinite and illite which are amongst the most common of clay minerals.

10 From 1962 to 1963 Tip 7 had dumped on it an appreciable quantity of separated fines from the froth flotation plant known as 'tailings'. Typically this material has a clay content of 25–30% and is essentially a silty clay. The clay minerals are those found in the parent shale and in addition there is fine coal dust present.

11 Tips 1 to 3, and 6 and 7 were built using a crane to dump the material from the wagons in which it came from the pit head. Tips 4 and 5 were built using an automatic (Maclean) tipping device which produced tips generally conical in shape and readily distinguishable from the other five. Despite the differences in the method of tipping and the changes which have taken place over the years in mining methods, all tips have basically an angle of repose of about 35°, except where collapses have occurred.

12 Bulk samples taken from the tips show the average overall water content to be about 8%, also without a great deal of variation. It is

worth noting, however, that in November 1966, subsequent to the disaster, driving rain against the face of the tip caused a mud-run to develop and a quantity of tip material flowed down the incline for a distance of several hundred feet. The fluid material appeared to be quite different from the parent tip from which it had flowed, but measurements showed that the chief basic difference was a rise in the water content from 8% to 14%. This profound change in behaviour had been accomplished by a very modest increase in overall water content and it emphasises how the behaviour of such materials is controlled by the fluidity of the fines. A better known example of the same phenomenon is the effect of a small quantity of water at a given stage on the workability of concrete.

13 A history of the whole of the Aberfan tip complex can be traced from the documents and other evidence produced, and notably from a series of aerial photographs taken at intervals from 1945 onwards which have been subjected to expert analysis first by the RAF (JARIC) and second by Fairey Surveys Limited (F.S.L.) to which reference is made in the following paragraphs.

Tips 4 and 5

14 It is evident from F.S.L. Fig. 1, a photograph taken in August 1945, that Tip 4, which had suffered a major collapse the previous November, was not a perfect cone prior to the slide, i.e. a movement which distorted the base had already taken place. It should also be noted that when the major failure occurred the bulk of the material stayed within the top section of the slide and did not travel a great distance, although a relatively thin tongue of material travelled some 1800 ft to within about 600 ft of the town.

15 From 1951 onwards Tip 5 (F.S.L. Fig. 3) shows a similar flattening of the surface in the region of the toe, and this becomes more marked in the 1960 photograph (F.S.L. Fig. 5).

Tip 7, 1958–1963

16 Tip 7 was started in 1958 upon a platform of colliery waste which had been dumped between Tips 3 and 4. By 1960 (F.S.L. Fig. 5) this area had been covered and the tip approached the bare hillside between Tip 3 and the run from Tip 4. Three years later in May 1963 (F.S.L. Fig. 6) that area had been completely covered over and the toe of Tip 7 was now opposite to Tip 3. Indeed a run from the toe had come opposite to the bottom of Tip 2, and, further than that, a streamer of wet tailings poured from the top of Tip 7 had run down the hillside almost opposite to Tip 1. By September 1963 (F.S.L. Fig. 7) the semi-liquid material being tipped from Tip 7 had spread over a wider area opposite to Tip 1 although the thickness was not very great.

Tip 7, 1963–1966

17 By November 1964 (F.S.L. Fig. 8) a considerable quantity of material from Tip 7 had flowed down the hillside adjacent to Tip 1, although the toe of the main tip was still opposite to Tip 3. By June 1965 (F.S.L. Fig. 9) this main tip had not altered greatly in plan. The tipping of wet tailings had ceased and a mantle of dry shale covered the tip shoulder fanning out from around the crane.

18 Two points of particular significance stand out in these photographs. First, there is the run from the toe of Tip 7 seen first in the May 1963 photograph (F.S.L. Fig. 6). There is no reason to connect this with tailings and it is probably normal tip material which has flowed under an increased water content. The cwm which developed behind it is visible through the remainder of the aerial photographs and it is not far from the point of emergence of the stream which accompanied the disaster. This gives the appearance of toe erosion but no stream is evident in this area in the earlier photographs. A stream is noted, however, by the Ordinance Survey, and if this had been tipped over it could well have had this result.

19 Second, there is the significant accumulation of material beneath Tip 7 seen first in the November 1964 photograph (F.S.L. Fig. 8). It would appear that a rotational slip had taken place some time previously and that part of the tip had travelled down the hillside until it was opposite to Tip 1. There is other evidence to indicate that a substantial slide may have taken place in November 1963. This again is not a tailings run, for right at the bottom there is a considerable volume of coarse-textured tip material with numerous pit props included in it. It is possible, however, that the material could have travelled on a lubricated mat of tailings. By November 1964 the major concavity, which would have resulted from a slide has certainly been largely filled in, but rising from the cwm the top of a failure surface can be clearly seen pointing towards the crane at the top of the tip.

20 When a rotational slide occurs there is comminution of the soil particles along the failure surface; the particles become aligned in the direction of the slide and the surface becomes polished. Even on natural slopes gradual movement may continue for many years after the initial slide has taken place. Similarly, after the presumed 1963 slide, continued tipping on top of a displaced wedge would tend to produce intermittent movements along the now existing failure surface. The crack visible at the top of the tip in June 1965 (F.S.L. Fig. 9) is a confirmation that such movements were taking place.

21 The effect of the grinding along the failure surface was to produce a clay with a low angle of shearing resistance (18°). A thin band of such a clay was subsequently found along a portion of the slip surface remaining in the body of the tip after the disaster flow when large displacements had taken place. This angle of $\emptyset$ is substantially less than that measured in normal tip samples (37°), in tailings (32°) or in the natural clay subsoil (29–40°).

22 The movements following the 1963 slip were small in extent. The tip and the underlying sandy clay were able to find new conditions of equilibrium without much movement, but the time came when these reserves were exhausted and a small deterioration in the conditions led to movements of a different order of magnitude. As, or immediately after, these were taking place, the evidence suggests that a volume of water escaped through the sandy clay in sufficient quantities to cause the conditions to deteriorate further still.

Stability analyses of Tip 7

23 By its nature a heap of tipped material resting at its angle of repose has a factor of safety only marginally greater than 1·0. But this refers to a shallow failure surface parallel to the face. It is to be expected that the factor of safety with respect to a deeper surface of sliding will be somewhat greater.

When a tip rests on a layer of soil weaker than the tip itself, a failure surface may develop which cuts through both tip and base and which therefore has a lower factor of safety than a surface entirely through tip material. Such a slip may be induced even more readily if the layer of soil beneath the tip is inclined, as on a sloping hillside.

24 The laboratory test results for the tip gave an angle ϕ of consistently between 37° and 39° which conforms well with the observed angle of repose of these tips. The laboratory values of ϕ for the layer of sandy clay on which the tip rests were found to vary between 29° and 40° and this reflects the variable nature of this deposit.

25 In this case theoretical analyses can give only an approximate guide to the stability of the tip on the hillside, for the glacial deposit on which it rests is extremely variable and there may also be weak zones in the tip itself. It is impossible to reconstruct the distribution of pore-water pressure prior to the disaster with any great accuracy.

26 Despite these accepted limitations, a series of stability analyses has been carried out for circular and non-circular potential slip surfaces and from the results certain general conclusions have been drawn. For these analyses a simplified profile was assumed on a flat-topped tip with an end face of 35° to the horizontal, 210 ft high from toe to crest, resting on a hillside sloping at 1 on 3½. The hillside was assumed to be covered with a 20 ft layer of soil overlying rock.

27 These calculations show that for the tip to stand on its foundation layer under the most favourable condition of zero pore water pressure present, the foundation layer must have an angle of shearing resistance, ϕ, of at least 32°. If positive pore pressures exist in the layer ϕ would have to be greater. Thus if a value of 0·1 is assumed for the pore pressure ratio in the vicinity of the toe, the value of ϕ would there have to be not less than 34°, which is in fact about the average angle from the laboratory test results for the silty clay.

28 These calculations show how a comparatively small increase in the water pressure within the sandy clay layer can lead to conditions of limiting equilibrium. Such a rise in pressure could readily be produced by water accumulating in fissures in the underlying Pennant sandstone.

29 It seems likely that the 1963 slip arose under these conditions. The intermittent movements which occurred up to the time of the disaster may be attributed to:
- (i) the continued loading from the top;
- (ii) a variable pore pressure in the underlying layer depending upon the recent rainfall and the inflow into the adjacent fissure system in the sandstone, and the ability of this water to escape both laterally and through the sandy clay into the lower layers of the tip material in the immediate vicinity of the toe;
- (iii) a decreasing ϕ on the now existing failure surface due to the intense shear strains developed there.

The early 12 ft to 20 ft movement of the tip on the morning of the disaster may be ascribed to a similar mechanism.

Energy balance limit analysis

30 The maximum velocity that the moving tip could achieve at the start of its slide was about 100 ft/sec, on the assumption that material fell freely from top to toe and was then deflected down the hillside. Even with such an initial velocity the mass would have come to a halt fairly rapidly unless its shear strength had altered radically at this stage.

Calculations show that even if ø dropped to 20° the mass would have come to a halt as the leading face of the material approached the canal embankment.

31 The fact that it went over the embankment suggests that the operative angle of shearing resistance during the slide was less than 20°, which means that increase pore fluid pressures must have arisen during the slide. It is possible that these could have been due to air but the evidence supports the simpler explanation that they were due to water.

32 This leads to the conclusion that the movement which followed the initial displacement had the nature of a flow slide. But for this to take place a small but significant rise in the overall water content of the moving tip material appears to be necessary, as has been indicated in paragraph 12.

33 The eye-witness accounts refer to :

(i) The hardened slurry below the base of the tip first breaking up, thereby indicating the deep-seated nature of the initial slide. This was later confirmed in the site investigation.

(ii) The toe of the tip being displaced accompanied by a volume of of water near to the middle of the face. As the bottom moved out so dry material from above it slumped down the tip and subsequently down the hillside, when it either mixed with the water or floated as islands of rather drier waste in a sea of mud.

34 The low initial density, and the grading and low clay content of the tip material, indicate that whilst on the move it would have mixed readily with an available water supply.

35 The theoretical studies outlined above indicate that the overall factor of safety of Tip 7 has for some years been at or about unity, and this is confirmed by the periodic small displacements which were taking place. They further point to the necessity for practical measures to ensure that excessive pore water pressures cannot build up beneath a tip under such conditions if displacements are to be avoided.

Summary

36 The evidence suggests that Tip 7 was built up to the limiting height at which it was stable on the hillside after which, with the addition of further material, persistent slipping occurred. The start of the disaster slide was of this nature but it changed in form to a flow slide capable of travelling a considerable distance under the influence of an additional source of water liberated from the hillside.

ITEM 3

Inquiry into the Aberfan Disaster

G. M. J. WILLIAMS MA MICE FASCE[1]

1 In November 1966 my firm was requested by the Parents' Association at Aberfan to advise them on matters arising in connection with this Inquiry.

2 I visited the tip complex at Aberfan on 9th November 1966, 15th November 1966, 22nd November 1966, 7th December 1966, and 20th January 1967. During these visits I walked over the entire complex on several occasions and I also walked along the courses of the various streams that drain the hillside around the tips from their several sources to the points where they join the River Taff. I examined what remained of the material that was displaced from Tip No. 7 during the slide on 21st October 1966, and inspected what remained of the properties that it damaged. I also examined the crater and the displaced material that remains from the slide of Tip No. 4 in 1944, and I observed the scars of smaller old slips in Tips Nos. 1 and 5.

3 I have visited the site of the tip slide that occurred on Cilfynydd Common in 1939 and I have walked over the material that remains from that slide.

4 During the course of this Inquiry I have studied a considerable number of documents relating to the disaster. These are listed in the attached Schedule and I have attempted to take them into account in reaching my conclusions. The salient facts, which are relevant to the study of this disaster from the viewpoint of a civil engineer, are set forth in Appendix 1.

5 Normally, in an investigation of this kind, I would expect to undertake a considerable site investigation, including digging trial pits, making borings and taking various types of samples of the soils and other materials involved, and these samples would be examined and tested in my firm's soil-mechanics laboratory. However, in this case it was not practicable for each of the represented parties to carry out a separate soils investigation on the site, and it was agreed that the Tribunal would conduct a single investigation under the direction of Professor Bishop and Dr Woodland and would make the results available to all the parties. Although I am aware of the findings of this investigation in general terms, I have not seen the full report on it at the time of preparing this proof.

6 In my opinion the evidence shows that the end of Tip No. 7 was in a state of limiting equilibrium for several years prior to the disaster. A slip-surface had developed inside the tip and there was constant movement along it. The location of this slip-surface appeared to be in the region where Tip No. 7 ceased to be buttressed by Tip No. 3; and the point where it reached the surface was manifested by the line of weakness across the top of the tip that has been mentioned by witnesses. I understand that the position of the lower parts of this slip-surface has been located during the site investigation.

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7 The pattern of movement over these years was that the tip achieved periods of equilibrium when the resistance to movement along the slip-surface balanced the gravitational forces tending to pull down the tip material above the slip-surface. Periodically this equilibrium was destroyed, probably by several means, including the deposition of further material on top of the tip, the erosion of material from the bottom and variation in the amount of water within the tip and in the pressure of this water. The tip would then move along the slip-surface and normally it would establish a new state of equilibrium after a movement of a few feet. These movements produced sinkings in the top of the tip, generally at the slip-surface, and they were observed by several witnesses.

8 On the morning of the disaster similar movements occurred, but on this occasion they initiated a liquefaction slide, the possibility of which was inherent in the situation. A large amount of material in the tip was temporarily transformed into a state where it behaved as a heavy viscous liquid that flowed rapidly down the mountainside, and did not come to rest until it regained its 'solid' properties. It was the occurrence of liquefaction that caused this slide to be so extensive and so destructive and dangerous.

9 This behaviour of the tip can be explained by well-established soil-mechanics theory. Soil mechanics is the scientific study of the behaviour of those materials that consist of an aggregation of discrete particles, and particularly of their interaction upon each other, and upon the fluid filling the voids between them. Thus, although in the everyday usage of the word, the material in the Tips would not be described as 'soil', it does come within the purview of soil mechanics, and in this proof the word 'soil' is used in a special technical sense to include all materials covered by soil mechanics.

10 It is very important to understand that in the type of material within these tips liquefaction can only occur if they are in a loosely packed condition and if they are substantially saturated, that is to say, the voids are filled with water rather than air. In such a material the effect of a disturbance will be to increase its density by causing the particles to pack more closely, thereby reducing the volume of the voids. In saturated material this can only happen if water is expelled from the voids. In a large mass this escape of water will take an appreciable time and the resistance to the outflow of water will set up temporarily high water pressures within the soil mass. This internal water pressure will reduce the forces acting between the soil particles and in an extreme case they may lose contact with each other entirely. This will suddenly reduce the friction between the soil particles, if not entirely eliminate it, and the soil will suffer sudden loss of strength. It will not regain its strength until sufficient water has escaped for the particles to regain contact in a denser configuration and for the excess internal water pressure to have dissipated. During the intervening period the soil will flow as a heavy liquid.

11 A dangerous and dramatic feature of liquefaction of this type is that it can be a progressive phenomenon. If it occurs in a part of a soil mass, the energy that becomes available through the movement of the liquefied zone can be sufficient to convert the surrounding zones in turn and the process proceeds almost instantaneously until all the soil that is liable to liquefy has done so.

12 It is now possible to understand the mechanism of the slide that caused the Aberfan disaster. Tip No. 7 contained a large amount of loosely tipped material and there was a volume in the lower parts of this mass that was saturated with water. On the morning of 21st

October 1966 there were several movements within the tip, as is evidenced by the settlement that occurred at the top, and shortly after nine o'clock there was apparently another movement, but in this case it took part of the saturated material past the point where liquefaction occurred. This initially liquefied material began to move rapidly, releasing energy which liquefied the rest of the saturated portion of the tip, and almost instantaneously the nature of the saturated lower parts of Tip No. 7 was changed from that of a solid to that of a heavy liquid of a density of approximately twice that of water. This was the dark glistening wave which several witnesses saw burst from the bottom of the tip. The upper part of the tip, not being saturated, did not liquefy, but some of it would be carried forward floating on the liquefied material, whilst the rest dropped into the hole that had been left in the face of the tip. Being of the nature of a liquid the whola mass then moved very rapidly down the hillside, spreading out sideways into a layer of substantially uniform thickness. As this happened water was escaping from the mass so that tha particles of soil regained their contact and the soil mass returned to its solid nature. Unfortunately a part of the liquefied mass flowed over the railway embankment and destroyed the schools and the houses in Moy Road.

13 This hypothesis of liquefaction explains the essential features of this slide, which are difficult to explain in any other way. These are, firstly, that a mass of soil that was capable of standing on a steep slope was suddenly changed into what eye-witnesses have properly described as a great wave of liquid which moved very rapidly down the hillside, spreading out horizontally over a large area; and secondly, that equally quickly it came to rest and exhibited sufficient strength for people to walk upon it and for it to stand at a steep angle in the classrooms of the Junior School.

14 It is important to understand that the quantity of water that had to be released from the soil to convert it from a liquid state back to the solid state was small. The evidence of the laboratory tests on samples of the material suggests that this amount of water need only have been 1% to 2% of the volume of the soil. Most of this water would have escaped as the soil was spreading out over the Coedcae Field and it explains why the slide was not accompaniad by large amounts of water when it reached the schools in Moy Road.

15 This movement differs considerably from that of a mud flow because mud is a mixture of soil and water which contains enough water to have substantially a liquid consistency at all times. Consequently, mud cannot stand in an embankment like a waste tip unless it is retained behind some kind of dam. Again, on coming to rest a mud flow retains its consistency, and it would not be possible to walk upon it, or for it to stand at a steep angle.

16 The movement of the liquefied tip material was followed by the release of water from two sources, and this water caused a number of secondary effects. These two sources were the broken water mains belonging to Cardiff Corporation and a spring which was revealed in the hole in the face of the tip that had been left by the slide. It has been suggested that in some way the flow of water from this spring carried the slide down the hillside, but the difficulties of this hypothesis become apparent when the rate of flow of water from the spring is considered in relation to the quantity of material that was moved. During the slide at least three million cubic feet of tip material moved down the hillside within a time which could not have exceeded three minutes. This corresponds to a rate of flow of some fifty thousand cubic feet per second (cusecs). It is unlikely that the flow from the spring exceeded 20 cusecs, and this is such a relatively small quantity that it could have had no effect on the slide at the time when it was occurring. The

importance of the spring is that it was probably the principal source of the water which had spread through the lower parts of the tip and had saturated it over a long period prior to the slide.

17 The disaster slip at Aberfan was not the first slip in the neighbourhood to involve liquefaction. There was certainly an element of liquefaction in the slip at Abercynon in 1939. This also came from a loosely deposited tip and there were springs beneath it which produced the necessary degree of saturation. The shape of the material deposited by that slip, as well as its rate of movement, are both consistent with liquefaction.

18 Following the slip at Abercynon in 1939 Messrs Powell Duffryn Limited produced a memorandum about safeguards to be observed in the siting and operation of rubbish tips to avoid slips. This memorandum was subsequently circulated by the National Coal Board in 1965, after only minor modifications.

19 The terms of this memorandum are a reasonable statement of the steps necessary to ensure the stability of tips in the light of the state of soil mechanics in 1939, but to re-issue them in 1965 ignored the fact that by then soil mechanics had become more of an experimental science. It was normal in 1939 to base the design of all foundations on tables of typical bearing pressure similar to Appendix 1 of this memorandum, but in 1965 most civil engineers concerned with the design of large embankments would regard this as a clumsy, wasteful approach. By 1965 the practice would have been to take samples of the ground, to measure their strength in the laboratory and to calculate the load that the tip could safely impose on the ground using the appropriate mathematical theory.

20 In 1944 there was a further slip in the neighbourhood that involved liquefaction. This slip was in Tip No. 4 at Aberfan and its extent was indicated on the Ordnance Survey Plan of 1957, although it has subsequently been largely obscured by later tipping and by the more recent slips. Again, the material in Tip No. 4 was loosely tipped and there was apparently water available to saturate part of it because the 1919 Ordnance Plan indicates that before the tip was begun, a stream commenced at a point very close to the centre of the crater left by this slip, and apparently there was no drainage to remove water from beneath the tip. Again, the extent and the shape of the material left by this slip can only be explained by a liquefaction slide on a steep slope.

21 It is possible, from the coal extraction records, that the slip of Tip No. 4 in 1944 was triggered off by mining subsidence, but there is no doubt that some small movement set up by the subsidence or otherwise caused the liquefaction of a considerable amount of material which then travelled over 2000 ft down the mountain to reach the Coedcae Field. However, any large mass of loose, saturated material is liable to liquefy on being disturbed, and the precise nature of the initiating disturbance is a secondary matter. Liquefaction could be initiated by any disturbance, whether due to an earthquake, mining subsidence, or to slipping due to shear failure of the tip and its foundation, as was the case in the disaster slip.

22 In October or November 1963 there was a movement of a considerable amount of material from Tip No. 7 and a large hollow was formed in the face of the tip. There appears to be a conflict of evidence as to how this hollow arose, but it was still visible when aerial photographs were taken on 10th November 1964. These photographs were subsequently used to make up the mosaic print, Document D5 (see

Fairey Surveys, Fig. 8, Ed.), but I have examined the original photographs with a stereoscope and the shape of the hollow shown on them is consistent with it being the scar left after a slip of a considerable amount of material from the tip.

23 I have been asked to express an opinion on what steps a competent, qualified civil engineer might have been expected to take before selecting the site for Tip No. 7 in 1958. His first steps would be similar to those taken in any site investigation. He would examine the ground and probably walk over it, and he would examine the geological and Ordnance Survey plans of the site and consult the geological sheet memoirs if he was not already familiar with the properties of the various formations in the locality. It would then be apparent that the proposed site was divided into an area where the new tip would be placed on previously tipped material in the valley between Tips Nos. 3 and 4 and an area where the new tip would extend to the south of Tip No. 3 on to virgin ground in the first instance and later on to the material that had slipped from Tip No. 4 in 1944. During these considerations he is of course bound to have observed the remains of the 1944 slip, both on the plans and on the ground. As he was engaged in considering the stability of a future tip he would have considered how Tip No. 4 had failed, and the only satisfactory explanation of the remains of this slip would have involved an element of liquefaction.

24 He would have examined the 1957 Survey plans during this exercise. As this indicates issues of water in the area of the new tip, it would be obvious that the ground water conditions would be an important consideration. Indeed there are many references to the desirability of providing drainage for tips, and the importance of drainage would certainly be in the mind of an engineer who had studied the behaviour of tips in South Wales.

25 At this stage it would be obvious that whilst a small amount of material might be safely placed in the valley between Tips Nos. 3 and 4, a major site investigation would be necessary to establish the measures that would be necessary to ensure the safety of the tip if it extended out of the valley, or if it were to rise to an appreciable height above Tip No. 3.

26 Such a site investigation must have indicated that the safe construction of a large tip on this site would have been a difficult and complex undertaking involving expense which I would expect to have been prohibitive.

27 Had any competent civil engineer been asked to investigate the condition of the tip after the movement that occurred in 1963 he would have made a similar investigation of the site and of the maps and records. In my opinion the tip presented such a vulnerable appearance at that time that any experienced engineer would have prohibited further tipping upon it until a complete investigation could have been made. Subsequent steps would have been to survey the shape of the tip and to make borings into the tip and into the hillside below to obtain samples of all the materials present and to examine the ground water conditions in detail. These samples would have been tested in a soil-mechanics laboratory to establish the properties of the various materials, and a stability analysis of the tip would have been made, using the information obtained from the tests and from the ground-water investigations. It is inconceivable that any experienced engineer would have agreed to the continuation of tipping until the tip regained its previous shape without extensive protective measures which would have been very expensive.

95 28 In 1965 the Divisional Chief Engineer asked for a report on each

active tip with reference to its safety and good management. I would expect an experienced civil engineer when faced with this task with respect to Tip No. 7 to commence by walking over the site, talking to the men who were concerned with the tip from day to day, and consulting the available plans and records, including the Ordnance Plan and the geological maps. Normally these initial considerations would enable him to identify the aspects of that particular tip that required further investigation by borings, laboratory tests and theoretical calculations. However, in the course of such a visit to Tip No. 7 in 1965 he must have seen signs of the previous slips in 1963 and 1944, he would see the irregular shape of the tip as indicated on photograph D6 (see Fairey Surveys, Fig. 9, Ed.), he should have learned of the creep of wet material down the hill in front of the tip and of the repeated settlements of the top. The evidence of the Ordnance Plan and geological maps should have suggested to him that there was probably a source of water under the tip and this would have been confirmed by the wet nature of the material in front of the tip and the manner in which fine material was being washed down by the streams. These observations should have made him conclude that the tip was in a potentially unstable and dangerous condition, and I would have expected him to require a detailed investigation to be made by experts urgently. Such an investigation would certainly have confirmed the dangerous condition that existed in the tip.

APPENDIX 1

INTRODUCTION

At the request of Messrs Morgan Bruce and Nicholas, Solicitors, acting on behalf of the Aberfan Parents' Association (later amalgamated with the Aberfan Residents' Protection Association, to form the Aberfan Parents' and Residents' Association) we have been asked to act as technical advisers to the Association in connection with the Tribunal set up to investigate the recent Aberfan disaster. This report summarises the basic factual information and evidence presently available to us, as listed in Appendix 2, and our conclusions and recommendations are based on this evidence.

We have, where possible, under the appropriate heading, inserted notes to the effect that our findings are in full or partial agreement with the data presented by the Tribunal's experts and that this information can be taken as also being our findings.

It is possible that evidence will be presented that may cause us to modify or change the emphasis of our findings.

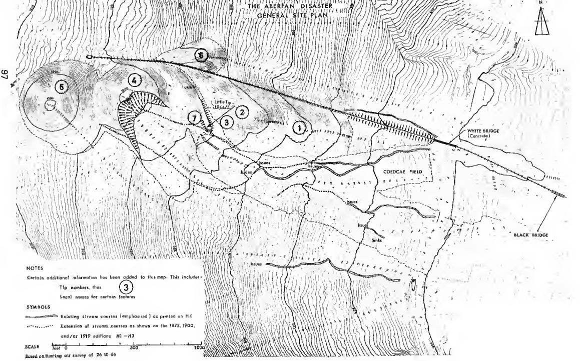
In this report, references to sources of information will be made by quoting between asterisks (*1*, see Appendix 2 list numbers for the sources).

If unqualified, the word 'site' refers to the area to the west of Aberfan covered by the tips and the immediately surrounding ground.

HISTORY

Tipping

The Merthyr-Vale Colliery was started in 1873 by the Nixon Navigation Company *1*. It was not until about 1916 that any tipping of colliery waste was undertaken to the west of the Glamorgan Canal; *2* this was after the construction of the White Bridge *3*. Three flat-topped tips (Nos. 1, 2 and 3 on Figure 3.1) were constructed 'en echelon' one above the other on the mountainside between about 1916 and 1933 *4*. There is evidence that before this tipping took place special drainage channels were constructed over the area proposed for tipping. These consisted of ditches filled with pitched stones and coarse gravel and overlain by protective flags *5*.


THE ABERFAN DISASTER
GENERAL SITE PLAN
N
1
2
3
4
5
6
7
Little Tip 1944/5
Issues
Issues
Issues
Issues
Issues
Issues
Issues
Smks
COEDCAE FIELD
WHITE BRIDGE (Concrete)
BLACK BRIDGE
NOTES
Certain additional information has been added to this map. This includes:
Tip numbers, thus 3
Local names for certain features
SYMBOLS
Existing stream courses (emphasised) as printed on H4
Extension of stream courses as shown on the 1875, 1900, and/or 1919 editions H1 – H3
SCALE
feet 0
500
1000
Based on Hunting air survey of 26 10 66

3.1 The Aberfan Disaster. General site plan.

In 1928 the Nixon Navigation Company went into liquidation *6*. The precise history between 1928 and 1935 is not really very clear but it appears that the colliery was run by Welsh Associated Collieries *7*. In 1933 a Maclean or Tippler tip was started somewhat higher up the mountainside and slightly to the west of Tip 3. This is marked No. 4 on Figure 3.1. In 1935 Powell Duffryn took over the colliery *8* and tipping continued on Tip No. 4 until 21st November 1944 when a major failure occurred in the tip and it was subsequently abandoned *9*. There is evidence that some surface drainage was installed relative to the stability of Tip 4 but it does not seem to have been in any way comprehensive and there is no evidence that drains exist beneath Tip 4 *10*. For a few months after the abandonment of Tip 4, tipping was carried out using horn rails on a site between Tips Nos. 3 and 4 next to the tram road or incline *11*. After this, sometime early in 1945, a new tip, No. 5 on Figure 3.1, was then constructed uphill of No. 4; this was also a Maclean tip *12*. During the construction of this tip the Powell Duffryn Organisation were absorbed into the National Coal Board, formed in 1947. Tipping continued on this tip No. 5 until it was abandoned in 1956 due apparently to the economic difficulties of tipping at a great height and also due to the fact that the tip was on fire (started 1953) and was causing a public nuisance *13*. A new tip was then started on the northern side of the tram road and was constructed as a flat-topped crane tip, the crane being electrically driven; the position of this tip, No. 6, is shown on Figure 3.1. Tip No. 6 was started in 1956 but had to be abandoned at Easter in 1958 because of its encroachment on the neighbouring farmers' land and because it was causing interference with the tram road *14*. It is understood that no drainage precautions or investigation of the site, with this in mind, were undertaken before or during the construction of this tip *15*. It was then decided to start a new tip marked No. 7 on Figure 3.1; this was again a flat-top crane tip. Before construction was started an area on the north-eastern corner of Tip No. 4 was made flat with a bulldozer and a parting put in from the main incline to the edge of this platform *16*. It is apparent from the evidence that little investigation was carried out and also that there were no drainage measures taken at all with regard to this tip *17*. The tip continued in the valley between Tips Nos. 3 and 4 until in about 1962 it extended beyond the southerly end of Tip No. 3. Waste disposal was then continued on this tip up to 21st October 1966. There is much evidence suggesting that from as early as 1960 the National Coal Board had intended to abandon this tip and start another further to the west either between No. 4 and No. 7 or to the west uphill of Tip No. 5. A number of schemes were suggested but none came to fruition *18*. It is understood that there was a scheme for tipping to the west of Tip No. 5 as long ago as 1950 but this was never undertaken, and there is evidence that Tips No. 6 and No. 7 were in fact 'stop-gaps' while permission was being obtained for a major tipping scheme *19*.

There is substantial evidence that natural springs and streams have been covered by tips, some by Tip No. 4 and others by Tip No. 7 *20*.

Previous Movements of Tips

There have been a number of major and minor movements in the complex of tips at Aberfan in the past (dates given here are as near as can be ascertained). Apart from the recent disaster the largest of these was the slide that occurred on 21st November 1944 in the first Maclean tip, No. 4 *21*. This was a very large slip which extended from the top of the tip in a 'tongue' stretching into the western half of field 8761, a total distance of 800 yards. There is much varying evidence with regard to the nature of this slip, the only common agreement being that rainfall had been heavy during the preceding days and that subsidence due to mining had affected or was affecting the area at that time; lastly that the failure happened and the slide was complete in a very short time probably during the night of 20th–21st November *H4, D1, K12, E6, 22*.

There has been considerable evidence given of movements in Tip 7, principally from 1963 onwards. Some of this evidence is conflicting but it appears that there have been three types of movement, that is to say, firstly, repeated settlement of the top of the tip towards its front edge; secondly, there has been a flow of very wet fine material from the tip down the hillside below; and thirdly, there is evidence that in October or November 1963 a considerable amount of material moved out of the face of the tip and went down the hillside leaving a recognisable hole. There appears to be a conflict of evidence about the magnitude or the significance of this latter movement, but there is an indication of it in aerial photograph D5 (see Fairey Surveys, Fig. 8), taken on 10th November 1964 *D6, 23, 24, 25*.

There is evidence that a number of minor movements have occurred on Tips Nos. 1, 5 and 7 over the years, other than that outlined above *D6, 26, 27*. The results of these movements can be seen in the shapes of Tips Nos. 1 and 5 to this day. There is also evidence which indicates that the top of Tip No. 7 did not advance very much between 1963 and 1966 although the toe continued to do so *28*; a number of the officials of the National Coal Board who were actively involved in the welfare of Tip No. 7 were unaware of this *29*.

There is a long history of tip movements at other collieries in South Wales, but of these, the one that occurred in 1939 at Cilfynydd is particularly relevant, and it has been referred to on a number of occasions during the Inquiry *30*. It has also been described in other publications, and it gave rise to a memorandum prepared by the Powell Duffryn organisation which subsequently became the basis of the memorandum issued by the Divisional Chief Engineer of the National Coal Board, Mr Powell, in 1965. General knowledge regarding tip slips was rather limited although some knowledge of some of the larger slips in tips in South Wales was possessed by Coal Board officials *30*.

Records and Control

The evidence shows that systematic inspection, other than from a mechanical viewpoint, of Tip No. 7 by qualified or authorised persons was not carried out *31* neither was there any delegation of responsibility *32*, no instruction to individuals *33*, no survey records *34*, and most of the officials who became involved with tip stability, particularly in Area 4, did not have the necessary experience or training to carry out an analysis of this sort. The only officials who did have such attributes are given in reference *36*. No enquiries were made as to the stability or as to what to look for to determine the stability of Tip No. 7 *37*. The only reports with regard to the progress and stability of this tip were associated with the tip workers and at Area level with the Area Mechanical Engineer as a result of the memorandum issued by the Divisional Chief Engineer, Mr Powell *38*.

There is evidence which suggests that in the days of Powell Duffryn, inspections of tips were both more frequent and more systematic *39*. Apparently the only working system in the National Coal Board with regard to tip inspection existed in the South Western Division Area 3, and this was not widely known or recognised *40*.

As the result of an incident at Ty Mawr tip in 1965 a document was issued in April of that year by South-West Division to all Areas requesting an immediate inspection of the active tips with regard to their stability. It contained a simple guide to the natural features and conditions which if pertaining might be of consequence. It was answered by all Areas with differing diligence and interpretation, and as far as Aberfan was concerned it was acted upon solely by the Area Mechanical Engineer who, with the exception of one or two senior officials at Area and Divisional level, was the only person actively concerned with it *41, 42*.

Flooding

There are a large number of statements relating to the fact that flooding occurred in the village of Aberfan after heavy rainfall from as long ago as 1951 ; further, that this flooding was the direct result of the interference with streams on the mountainside by tip material *43*, and the resultant carrying down of this material, causing the blockage of culverts and the silting up of waterways. General evidence of flooding *44* has been given as has more specific evidence with regard to the blockage of culverts and drains by waste material, particularly from Tip No. 7 *45*.

The only positive action prior to 21st October 1966 taken by the National Coal Board to prevent this flooding occurring was to construct two drainage channels below Tip No. 7 running from south to north across the material from the 1963 incident *46*. The inefficiency of the measures taken, the complaints to the Merthyr County Borough Council and to the National Coal Board regarding flooding and stability and their combined reluctance to take action or responsibility, are all recorded in the evidence *47*.

The Slip of 21st October 1966

Since the movement which happened in late 1963, minor slips, tension cracks, areas of local subsidence and malformations in Tip No. 7 have been regularly noted and in some instances commented upon, as has the interference with drainage and the subsequent flow of water from or close to the base of this tip *20, 27, 28, 48*.

On the morning of 21st October 1966 at about 7.30 a.m., it was noted and subsequently reported that a large section of the top of the tip had subsided about 10 ft *49*; within the next hour and a half this subsidence had increased to about 20 ft. At approximately 9.15 a.m. a major structural failure was seen in development *50*. The consequent flow of material in an apparently heavy viscous fluid form was observed until it disappeared into the mist some 50 to 100 yards from the top front edge of the remaining tip; this movement took only a few seconds or at the most a minute, estimates of the speed of movement are very variable, but it seems from the evidence that the overall velocity from the moment of failure to the arrival of the slip in Aberfan was at least 15 miles per hour and was probably considerably greater during the early stages *51*. The flow of material continued downhill to the canal and railway embankment on the western edge of the village; it crossed these *52* and then, with lessening velocity, it overwhelmed the Primary School and the houses in Moy Road, finally coming to rest near to the position marked on *H5* (see Fig. 42. Ed.). After the initial movement all the evidence available suggests that when the material first came to rest it had a substantially dry appearance and there was little free water to be seen *53*. The height of the material forming this first onrush was estimated to be between 20 and 30 ft *54*. At some time during this initial movement the water mains were fractured, releasing about 70 cubic feet per second of water *55*. Water from both the mains and from the stream issuing from the slip cavity combined to increase the water content and fluidity of the surface part of the slipped mass *56* although it appears that this action was largely confined to the northern part of the southern limb of the slide. At about

9.45 a.m. a substantial movement of wet material occurred and this was preceded or associated with an increase in the volume of water issuing from the tip material, particularly in the area of the Secondary School *57*. The descriptions of the condition of the slipped material after this second movement vary among themselves. However, it has been clearly established that although it was, at this time and subsequently until noon, very wet on the surface due to the mains water and stream water *56*, it was possible to walk on it and to cross it on foot *58*. It is understood that the mains water was turned off between 11 and 11.30 a.m., and that the stream was diverted between 2 and 3 p.m., and that the material was drying out subsequent to the former and latter events *59*. There is variable evidence with regard to the cessation of movement of the slip but it would appear to be fairly certain that only creep occurred after 11 a.m. and that to all intents and purposes movement had ceased by 1 p.m. *60*.

NATURAL FEATURES AND RECORDS

Geology and Soils

We have agreed in discussion with Treasury experts but have not seen or agreed their final Report.

Topography and Drainage

The natural topography of the site forms the east-facing slope of a steep-sided glaciated valley cut into a flat plateau. The tip area extends from the 600 ft contour to around the 1200 ft contour. The valley bottom is at about 400 ft above Ordnance datum. The slope of the valley side has a gradient of about 1 ft vertical in 4 ft horizontal in the tip area (see Figure 3.1).

The main drainage course is that of the River Taff. Draining into this river are a large number of small streams flowing at right angles to the Taff. The sources of these streams are closely related to the geological sequence of underlying rocks.

The close correlation between the spring lines and geology is a function of the permeability of the rocks through which the water is draining. The sandstones are relatively permeable and therefore act as aquifers, whereas the underlying bands of coal seams, seat earths and shales are relatively impermeable, forming a drainage barrier. The water within the permeable sandstones therefore tends to emerge at the ground surface along the lines of outcrop of these permeable/impermeable interfaces.

There is evidence which confirms that a number of streams did exist and have existed up to the present day on this mountainside in the tip complex area and that these streams and springs are perennial *61*.

As can be seen from Figure 3.1, some of the springs and streams have been affected by the tipping, and also their lower courses have been culverted and piped during the development of the village of Aberfan. It is also possible that subsidence has to some limited extent affected the surface drainage *K12*.

Meteorology

Agreed Report E6. (See A. Bleasdale, 'Meteorological conditions relating to the Aberfan Inquiry', Item 7 below. Ed.)

Seismic Data

Agreed Treasury Experts Report. (See A. W. Bishop *et al*, 'Geotechnical investigation into the causes and circumstances of the disaster on 21st October 1966', Item 1 above. Ed.)

Subsidence

Agreed Report K12. (See K. Wardell and R. J. Piggott, 'Report on Mining Subsidence', Item 6 below. Ed.)

MATERIALS TIPPED

The materials deposited in Tips Nos. 1, 2, 3, 4, 5 and 6 consisted of coarse and fine sandstone and shale with some small coal, washery shale together with ashes, clinker, colliery rubbish etc *62*.

Between 1958 and February 1962 the same material was deposited on Tip No. 7 *63*. During this period additional waste material from the newly installed froth flotation plant was being sent to another tip site called the Lucy *64*. This material was a slurry-like substance. Between February 1962 and February 1965 similar slurry material was tipped, but in addition vacuum dried froth flotation waste (tailings, Ed.) was tipped on Tip No. 7 despite attempts by the colliery manager and the local Council to get this material sent elsewhere *65*.

The waste product from this process consisted of a gel of the very fine waste materials and it was known to be both difficult to handle and to be unstable if tipped in bulk *66*. Between February 1965 and October 1966 only materials similar to those tipped between 1958 and February 1962 were sent to Tip No. 7. There is very variable evidence regarding the various quantities of materials tipped at various times; however, it would appear that at the peak of tipping in late 1962/early 1963 up to 500 tons per day were tipped in a double shift and that 80 trams (i.e. 1 in 6 nominally 1 ton capacity) of tailings would be a fairly normal proportion of such a daily load *67*.

APPENDIX 2

Note: All references to letters followed by numbers, viz. D1, H4, E6, K12 etc, are references to Treasury Documents. All single number references are listed below and relate to the Transcripts of the Tribunal Proceedings.

Editor's Note

Application to refer to documents such as D1, H4 etc and the Transcripts of the Tribunal Proceedings may be made in writing to the Treasury Solicitor, Treasury Solicitor's Office, 3 Central Buildings, Matthew Parker Street, London SW1.

Copies of the Transcript of the Tribunal Proceedings are also held by the Building Research Station, Imperial College of Science and Technology, London, and the University College of Swansea: application to refer to these copies should be made to the respective librarians.

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31	L. Davies	6	293, 303, 329, 330
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	D. Colston	14	723
	D.J. Maybank	15	730
	W. Pierce	15	755–6
	W.R. King	16	802, 806
	T.J. Davies	17	909
	R.V. Thomas	17	916
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	J.S. Wynne	23	1261
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	J. Baker	27	1441
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	D.L. Roberts	32	1766
	Ditto	33	1783
	Ditto	34	1839
	T. Wright	42	2331
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	C. Jones	45	2456
	D.L.J. Powell	47	2607
	G. Morgan	50	2781

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	A.D. Laidlow	22	1187/8, 1190, 1200, 1202
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	J.S. Wynne	23	1257–8
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33	L. Davies	6	326–7
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34	A. Way	20	1083
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36	A. Way	21	1086
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37	L. Davies	6	284
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	C. Jones	45	2480
	G.A. Jones	45	2515

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39	L. Davies	5	275
	D.8. Jones	11	553
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	G. Morgan	48	2690
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40	P. Grant	40	2213
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	C. Jones	45	2475
	G.A. Jones	46	2536
41	D.L. Roberts	33	1770, 1818–9
	Ditto	34	1852
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	G.A. Jones	45	2509
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42	R.N. Lewis	22	1181–2
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	H.L. Davies	4	224
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	E.R. Griffiths	12	622
	C. James	13	635
	V.C. Jones	13	693
	W.R. King	15	790
	Ditto	16	793, 811, 819–20
	T.J. Davies	17	911–2
	R.V. Thomas	18	946
	Ditto	20	1021
	R.N. Lewis	21	1109, 1126
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	J.S. Wynne	23	1245
	T. Griffiths	26	1401
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45	K.J. Davies	3	132
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	C. James	13	635
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	Ditto	31	1662–3
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	D.L. Roberts	32	1759
	R.E. Exley	36	1941
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	W.R. King	16	793
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	J.S. Waters	20	1059
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	D.8. Jones	9	482
	R.L. Short	12	604
	D. Colston	14	711, 719, 720
	W.R. King	16	796, 822
49	L. Davies	5	265–6
	Ditto	6	306, 314–5
	G.E. Brown	7	360–1
	D.B. Jones	9	483
	W. Pierce	15	785
	R.V. Thomas	18	926, 979
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50	K.J. Davies	3	127
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	H. Watkins	3	149
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	W.R. King	16	831
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54	T. Griffiths	2	102
	E.G. Rees	2	108
	G. Groves	2	111
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	E.G. Rees	12	615
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57	R. Wilson	2	113
	K.J. Davies	3	129, 134
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	W.R. King	16	800, 824, 830
58	R. Wilson	2	112, 115
	C. Jones	3	123
	W.T. Roberts	4	205
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59	T. Griffiths	2	102
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	J.S. Wynne	24	1276
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65	E.C. Jones	9	467
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	Ditto	33	1790–1798
66	L. Davies	5	259
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	R.V. Thomas	18	945/6, 978
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	Ditto	22	1159
	J.S. Wynne	23	1245
	W.J. Strong	26	1389
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67	L. Davies	6	311
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	W. Pierce	15	774
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Technical References

Geological

A A Dictionary of Geology, G.W. Himus, Penguin Reference Books
B Geology of the South Wales Coalfields, Part IV, Pontypridd and Maesteg, 3rd Edition, Dr Austin W. Woodland and W.B. Evans
C Colliery borehole records from Library of Geological Survey, London
D British Regional Geology—South Wales, 2nd Edition, J. Pringle, DSc (Wales), and T. Neville George, DSc, PhD

Various

E A Dictionary of Civil Engineering, John S. Scott, Penguin Reference Books
F British Standard Code of Practice CP 2001 (1957)—Site Investigations
G British Standard Code of Practice CP 2003 (1959)—Earthworks
H Landslides in South Wales Valleys, Professor George Knox FGS, MIME, Proceedings of South Wales Institute of Engineers, March 1927
I Ground Movement and Control of Collieries, Professor John Sinclair MEng, PhD, MIMinE, Pitman 1963
J The Stability of Embankments of Frictional Material Retaining a Low-Frictional Hill, A.H. Naylor, J.G. Stuart and N.K. Edu. Geotechnique, 11:2:114–120 (1961)
K Landslides and Related Phenomena, C.F.S. Sharpe, Columbia University Press N.Y. (1938)
L Mechanisms of Landslides, K. Terzaghi, Engineering Geology (Berkey) Volume, Geological Society of America, November 1950, pp 83–123
M Stabilization of an Ore Pile by Drainage, K. Terzaghi and R.B. Peck, Proceedings ASCE, Vol. 83, No. SML, January 1957, pp 1–13
N Landslides and Engineering Practice, Highway Research Board Special Report No. 29 (1958)
O The Stability of Colliery Spoilbanks, G.L. Watkins, Colliery Engineering, November 1959, Vol. 36, pp 493–497
P Attorney General versus Cory Bros and Company, House of Lords, 27th January 1921

APPENDIX 3

Note on Liquefaction Slides

The Liquefaction Process

Natural or artificial slopes of granular material only remain stable if there is sufficient 'frictional' force between the solid particles of which they are composed. The 'voids' between the particles may contain water or air, or both, but the solid particles are in contact to provide friction.

The state of 'packing' of the solid particles may be loose or dense, or intermediate. A slope may be stable even if it is in a very loose state. However, in some circumstances, if the material is disturbed its particles may re-arrange themselves into a denser state. For example, consider idealised spherical particles in a cubical container (Figure 3.2).

If the particles are loosely packed and the voids are full of water, the water surface in the above example will obviously remain at a–a; the particles in B have 'shaken down' into the water but the material is again in a stable condition.

With a material which has a grading similar to that of a fine sand or coarse silt, the 'permeability' may be so low that, when the material is disturbed, the water in the voids cannot flow quickly and so the solid particles do not remain in contact with each other. This condition is illustrated in C (Figure 3.3), although it should be realised that the particles would be much smaller than they are drawn if a low-permeability condition exists. (The diagram does not in any case represent the particle structure of a real soil or tip material, but the principles discussed apply equally to these.) In the state shown in C, there is no contact between the solid particles and therefore no friction between them; the material is unstable.

If such a material exists as an embankment, instead of being confined in a box, the embankment will slump when its structure is disturbed; and if the embankment is on sloping ground, the slumped material will flow down the slope, like a heavy liquid. It will stop flowing when the particles again achieve sufficient contact to build up enough friction between themselves for the new profile of natural ground and embankment material to be stable. Within a few minutes, the material reverts from its temporary fluid condition to a 'solid' condition, more stable than that from which it started.

The initial disturbance of the particles, which causes the unstable condition in which a liquefaction slide can take place, may itself result from any of a number of causes. Frequently the cause is an 'ordinary' slip due to the build-up of stresses during the construction of an embankment (or tip). Other possible causes are explosion, earthquake and subsidence; a flow of water may also act as the trigger.

Information about Liquefaction

Although there have been no well-publicised cases of liquefaction slides in this country, the phenomenon is covered in the standard literature of soils engineering. A textbook known to most students of civil engineering since 1950, and probably known at least by repute to all practising civil engineers, is *Soil Mechanics in Engineering Practice*, by Terzaghi and Peck (Wiley and Chapman and Hall, 1948). Almost as well-known are *Fundamentals of Soil Mechanics* by Taylor (Wiley, 1948) and *Soil Mechanics, Foundations and Earth Structures* by Tschebotarioff (McGraw-Hill, 1953). All these discuss the phenomenon and give references to more specialised treatments of it; other references are readily accessible in civil engineering literature. A number of references are listed in the attached bibliography.

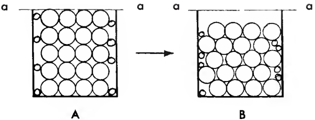

Fig. 3.2.

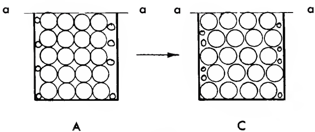

Fig. 3.3.

References to Liquefaction

1. *Casagrande, A.* 1964
   'The Role of the "Calculated Risk" in Earthwork and Foundation Engineering'
   2nd Terzaghi Lecture, ASCE, 21st October 1964
2. *Middlebrooks, T.A.* 1942
   'Fort Peck Slide'
   Trans. ASCE 1942, pp. 723–742
   (Note: Discussion particularly relevant, pp. 752–755)
3. *Hazen, Allen* 1920
   'Hydraulic Fill Dams'
   Trans. ASCE 1920, pp. 1713–1745
4. *Terzaghi, K.* 1956
   'Varieties of Submarine Slope Failures'
   Harvard Soil Mechanics Series No. 52
5. *Geuze, ECWA* 1948
   'Critical Density of Some Dutch Sand'
   Proc. 2nd ICSMFE 3 : 125–130
6. *Koppejan, A.W., van Wanelen, B.M., and Weinberg, L.J.H.* 1948
   'Coastal Flow Slides in the Dutch Province of Zeeland'
   Proc. 2nd ICSMFE 5 : 89–96

7. *HRB* 1958
'Landslides and Engineering Practice'
HRB Special Report No. 29
(Note: Particularly Chapter 3)
8. *Savage, C.N.* 1950
'Earthflow Associated with Strip Mining'
Mining Eng., 187 : 3 : 337–339
9. *Ivanov, P.I.* 1962
'Liquefaction of Sand' (In Russian)
Moska Gosenergoizdat
10. *Florin, V.A., and Ivanov, P.I.* 1961
'Liquefaction of Saturated Sandy Soils'
5th ICSMFE, 1 : 107–112
(Note: All references given in this paper are in Russian)
11. *Huang, Wen-Xi* 1961
'Investigation on Stability of Saturated Sand Foundations and Slopes against Liquefaction'
Proc. 5th ICSMFE, 2 : 629–632
12. *Stroganov, A.S.* 1961
'Visco-plastic Flow of Soils'
Proc. 5th ICSMFE, 2 : 721–726
13. *Terzaghi, K.* 1926
'Erdbaumechanik', pp. 344–352
14. *Terzaghi, K.* 1950
'Mechanism of Landslides'
Engineering Geology (Berkey) Volume
Geol. Soc. Amer., Nov. 1950, pp. 83–123
15. *Ehrenberg, J.* 1950
'The flow of a sand tip in a lignite mine' (In German)
'Bautechnik' No. 19, Berlin, 1933
16. *Casagrande, A.* 1936
'Characteristics of Cohesionless Soils Affecting the Stability of Slopes and Earth Fills'
Journal Boston Soc. Civ. Engrs., 23 : 13–32

One passage in reference 16 is particularly apposite and reads as follows:

'The lack of stability of very fine-grained, saturated materials must also be considered in the placing of spoil banks of chemical wastes which often consist of very fine powders. Excepting for a dry surface crust the voids of such materials are filled with water. The large capillary pressures render it seemingly very stable, capable of standing on high vertical banks. Yet disturbances of any sort or the formation of shrinkage or tension cracks with subsequent infiltration of surface water resulting in deformations of the mass, will result in local liquefaction of the material which may spread quickly over large areas and lead to a slide. . . . even large seepage pressures may result in a tendency to reduce the volume due to an adjustment in the structure reducing the shearing resistance to such a point that the whole mass can flow like a liquid under the effect of the seepage pressures.

And:

The density in the loose state of many cohesionless soils, particularly medium and fine uniform sands, is considerably above their critical density. Such materials in their loose state tend to reduce their volume if exposed to continuous deformation. If the voids are filled with water and the water cannot escape as quickly as the deformation is produced, then a temporary transfer of load on to the water takes place and the resulting reduction in friction impairs the stability of the mass, which can lead, in certain cases, to a flow slide.'

Geological Report on the Aberfan Tip Disaster of October 21st, 1966

A. W. Woodland BSc PhDFGS[1]

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6. Conclusions regarding Tip No. 7 disaster slide

Appendix I. Ground-water conditions in the Pennant Sandstone

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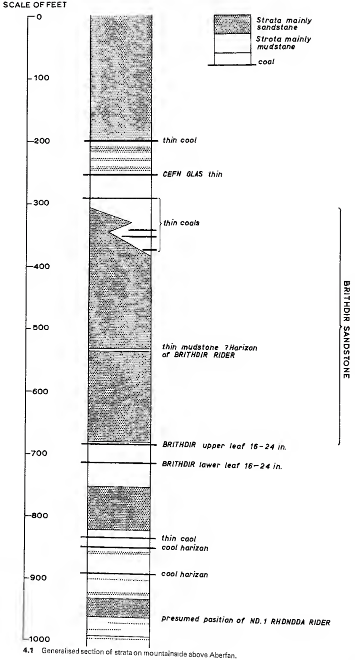
[1] Assistant Director of the Geological Survey of Great Britain (now incorporated in the Institute of Geological Sciences of the Natural Environment Research Council).



4.1 Generalised section of strata on mountainside above Aberfan.

1. GEOLOGY OF THE MOUNTAINSIDE ABOVE ABERFAN

1.1 **Solid Rocks**

1.1.1 Rocks of the highest division of the Coal Measures, referred to in South Wales as the Pennant Measures, form the hillside of Mynydd Merthyr above Aberfan and crop out on its slopes. They consist predominantly of a number of thick massive well-jointed sandstones, known as 'pennant'. These are separated from one another by varying thicknesses of mudstones or shales, which commonly contain thin coals and their underlying seatearths or fireclays. In general the outcrops of the mudstones lie immediately above comparatively broad shelves formed by the tops of the main sandstones. The main parts of the sandstone outcrops give rise to steeper slopes.

1.1.2 During the course of investigations carried out since the disaster several boreholes have been drilled which prove the sequence of strata in greater detail than was previously known. The results of these boreholes are incorporated in the vertical section given below, which now serves as the generalised succession for the hillside in the immediate vicinity of the tip-complex. This is shown graphically in Figure 4.1.

	ft
Massive sandstones	200+
Coal, thin and impersistent	—
Mudstones and sandstones in alternating layers	43
Coal CEFN GLAS	thin
Mudstones	31
Coal	thin
Mudstones and sandstones in alternating layers	51
Mudstones with two thin coals	38
Massive sandstones	about 150
Mudstone, ? at horizon of BRITHDIR RIDER	5
Massive sandstones	140
Mudstone	6
Coal BRITHDIR upper leaf	1½
Mudstones	25 to 35
Coal BRITHDIR lower leaf	2
Mudstones	36 to 45
Massive sandstones	70
Mudstones with thin coals	116
Sandstones with thin mudstone bands	30
Believed horizon of NO. 1 RHONDDA RIDER	—
Mudstones and siltstones	45+

1.1.3 The surface outcrops of these strata, generalised somewhat into main sandstone and mudstone developments, are shown on the agreed Geological Plan, Figure 4.2 (in wallet). The broken lines used as boundaries denote a degree of uncertainty in recognising the precise positions of stratal junctions on the ground. Mapping suggests that the mudstones immediately above the Cefn Glas are abnormally thick in the above section and that the lower part of the mudstones below the Cefn Glas passes laterally into massive sandstones where traced laterally to both north and south.

1.1.4 Reference to the plan shows that the tip complex lies mainly upon the outcrop of the sandstones which separate the Brithdir and Cefn Glas horizons. The No. 1 Rhondda Rider Coal probably crops out in the bottom of the valley beneath glacial deposits; the Upper Brithdir outcrop gradually rises north-north-eastwards from the neighbourhood of the old Hafod Tanglwys Level and passes beneath the tip-complex at about the junction of No. 1 and No. 2 tips. No Brithdir Rider Coal has been proved in the vicinity of the tip-complex, though it is known at several points on the western slopes of Mynydd Merthyr overlooking the Cynon Valley. Boreholes R4 and R6 both proved thin mudstones (associated in the latter case with non-marine shells) about 145 ft above the Brithdir upper leaf, and these may well represent a continuous development of thin mudstone at the horizon of the Rider Coal. The outcrop of this mudstone appears to pass beneath the south-eastern sector of Tip No. 4. The outcrop of the Cefn Glas Seam follows a course roughly parallel to that of the Brithdir, and its associated mudstones crop uphill and to the west of Tip No. 5.

1.1.5 A further 1700 ft of Coal Measures underlie the valley floor at Aberfan and the main workable coals occur in the lower part of these.

1.2 **Superficial Deposits (Drift)**

1.2.1 The lower slopes of the hillside are covered by deposits left behind by the glacier which filled much of the Taff Valley during the last glaciation. These deposits consist of stiff clays with many stones (till or boulder clay) which pass gradually down-hill into clayey gravels. The matrix of the boulder clay is a compact gritty clay in which are crowded many boulders, cobbles and smaller fragments of hard rocks. Towards the lower slopes the matrix becomes increasingly sandy and the contained stones more rounded; under these conditions the deposit is shown on the published geological maps as sand and gravel though the boundary between these and the boulder clay is quite arbitrary. In its lithology, and presumably also in its physical properties, the typical boulder clay of the South Wales valleys differs appreciably from the genetically related boulder clays of soft-rock lowland regions. In general the glacial deposits form a valley-fill which is recognisable as a sloping terrace above which the solid rocks of the hillside emerge to form more steeply rising ground. The limits of the boulder clay and associated gravel are shown on the Geological Plan by a pecked line. This convention is adopted because by their very nature it is not possible to delimit such superficial deposits with the same precision as the more geometrically arranged solid rocks. In the Aberfan area a tongue of boulder clay extends up the valley-side to about 900 ft O.D. behind Hafod-tanglwys-uchaf, and underlies the southern and eastern margins of the tip-complex. Beneath the spoil the margin depicted is imprecise because the tip was in being at the time of survey. The tongue covers the outcrop of the Brithdir coals in this area and complicates the local hydrogeology (see below).

1.2.2 The thickness of the glacial deposits varies considerably and is largely controlled by the contours of the underlying surface of the solid rocks. In the bottom of the valley 68 ft of sand and gravel were proved in Merthyr Vale shafts, and thicknesses in excess of this are not unlikely locally. In general the deposits thin out up-slope though not in a regular fashion.

1.2.3 Further superficial deposits, known as 'head', plaster most of the hillside above the limit taken for the boulder clay, extending over the boulder clay itself. This 'head' is formed by the downward creep and wash of debris resulting from the weathering of the rocks cropping out above. If the rocks forming the slopes above are mainly sandstones the head itself is sandy and permeable; if thick mudstones are interbedded with the sandstones the matrix of the head is likely to be clayey and the deposit as a whole relatively impermeable. These deposits are virtually ubiquitous on the valley slopes in South Wales, and for this reason they are not depicted on the maps. They have accumulated rather more thickly on the gentle slopes of the shelves which mark the tops of the main sandstones, and around the tip-complex they are especially extensive on the slopes beneath the Cefn Glas outcrop. Locally, thin boulder clay is associated with the head on shelves well above the main glacial fill, but under these conditions the two deposits are inseparable by normal mapping methods. Thicknesses of head are variable, but they appear to be generally greater on the south side of the tip-complex than to the north. In the latter area thicknesses of 5 to 10 ft generally prevail, while to the south 20 ft or more may occur.

1.3 **Structure**

1.3.1 The structure of the rocks underlying Mynydd Merthyr is relatively simple and is best understood by reference to the Horizontal Sections A–B and E–F (Figures 4.3 and 4.4, see wallet). In general the strata at surface dip at about 1 in 12 towards south-east by south. This has been confirmed by boreholes from which measurements varying from 1 in 9·5 to 1 in 13·5 in direction 139° to 149° azimuth have been derived. These dips agree in general with those proved underground.

1.3.2 No significant faults have been proved to affect the ground immediately beneath the tip-complex. The surface trace of the Kilkenny Fault lies rather more than 600 yd to the south-west of Tip No. 5; a throw of almost 300 ft down north-east has been proved at depth west-south-west of Merthyr Vale shafts. Recent site investigations have proved at surface a sub-parallel fault 1400 to 1800 ft north-east of the Kilkenny Fault, throwing down south-west about 150 ft in the area west of the tip-complex. In the Five-Feet Seam workings north-west of Merthyr Vale shafts a fault throwing down south-west—the 'Twenty-seven Yard Fault' of the Wardell-Piggott report—has been proved parallel to the Kilkenny Fault and about 1600 ft north-east of it. The underground position of this fault lies beneath the tip-complex, but it has not been detected at surface.

1.3.3 The Pennant sandstones are strongly jointed in at least three characteristic directions. The best-developed joints trend approximately 120° to 130° azimuth. A well-marked but subordinate set of joints is aligned roughly at rightangles at approximately 30° to 40° azimuth. A third set, not nearly so clearly defined, trends very nearly west-east. These measurements are based on the Brithdir sandstones exposed in the quarry south of Aberfan Cemetery and on the outcrops around Cnwc, nearly half a mile north of Tip No. 5.

2. HYDROGEOLOGY

2.1 A detailed analysis of the ground-water conditions in the Pennant sandstones is set out in Appendix I of this report; this has been prepared by Mr D.A. Gray, Chief Geologist of the Water Division of the Institute of Geological Sciences, and is based on measurements taken in boreholes drilled since the post-disaster investigations began and on data provided by the National Coal Board and by the Meteorological Office. The following account takes into consideration the main conclusions there expressed.

2.2 The mudstones of the Coal Measures are poor aquifers. The Pennant sandstones, on the other hand, although not porous, are strongly jointed and thus very permeable to water. In areas where the joints are open, the sandstones are capable of containing and transmitting considerable amounts of fissure-water. Rain falling on the outcrops of such sandstones percolates downwards through the joints or fissures and along planes of bedding until it reaches a layer of virtually impermeable mudstone or clay-rock, above which it flows laterally through the fissures to emerge at surface as seepages and springs. The seatearths or fireclays lying immediately beneath coals form such impermeable layers, and on the hillsides of the South Wales Coalfield, coal seams cropping at the bases of major sandstones are commonly marked by lines of springs. Although boulder clay may allow the percolation of appreciable amounts of water, it is, nevertheless, far less permeable than well-fissured sandstone. Where the base of a sandstone is masked by boulder clay of sufficient thickness, the release of water from the fissures is impeded; under these conditions water builds up within the sandstone, until it overspills at the upper limit of the boulder clay. Where the rock-head spring-line is concealed by permeable drift deposits, e.g. scree or sandy head, the water emerging from the sandstone may flow downhill some way before it emerges through the drift at a point lower on the slope than might be expected.

2.3 Little is known of the precise factors which determine the location of major springs, but they must clearly be related to the incidence of master-joints and fissures within the rocks. Where these are controlled by tectonic influences, the same structural feature, e.g. a fault or crush-zone, may produce springs more or less one above the other in successive sandstone aquifers and these may feed and be aligned along the same water-course.

2.4 On the mountainside above Aberfan both the Brithdir and Cefn Glas outcrops, in particular, are associated with springs of varying magnitude. Several strong springs emerge along the Cefn Glas horizon above the tip-complex, some, though by no means all, of which are indicated on the Ordnance Survey maps. The presence of these springs indicates that the effects of mining subsidence have not been sufficiently drastic to allow the water contained in the Cefn Glas Sandstone to drain through the underlying mudstones into the Brithdir Sandstones beneath. Immediately west of Tip No. 5 much of the seepage water from the Cefn Glas outcrop is re-absorbed through the head deposits and presumably finds its way into the underlying sandstones, though farther south along the hillside several of the Cefn Glas springs give rise to sizeable streams.

2.5 The Brithdir Sandstone is clearly a major aquifer. Strong seepages can be observed along the line of outcrop north of the tip-complex toward Cnwc, but in the neighbourhood of the complex itself the tongue of boulder clay behind Hafod-tanglwys-uchaf, referred to above, has effectively sealed points of emergence at the base of the sandstone. Consequently in this area water would be expected to build up in the sandstones behind the boulder clay and to spill over as springs at its upper margin. Similar occurrences are common along many of the South Wales Coalfield valleys and these conditions must have set in soon after the disappearance of the valley glaciers many thousands of years ago.

2.6 A further potential spring-line is controlled by the position of the thin mudstone at the horizon of the Brithdir Rider Seam, and other minor seepages are produced by impersistent mudstones occurring sporadically within the major sandstones.

2.7 There is now no satisfactory proof in the legal sense of the presence of springs beneath the Aberfan tip-complex prior to tipping, for no reliable observations going back to this date have been recorded. The spring positions shown on the various editions of the Ordnance Survey maps do not provide conclusive evidence of the full story. Cursory examination of the Aberfan hillside at the present day shows that by no means all observable springs are marked. Nevertheless, those that are shown must illustrate actual emergences of water at a particular date, but the omission of others must not be taken as indicating even non-emission on the day of survey. Springs issuing along the course of existing streams must be particularly liable to oversight. Nor do all springs flow perennially, and the fact that no springs are seen in the dry conditions of summer must not be taken as indicating that they do not flow in wet conditions during the winter half of the year.

2.8 Several witnesses, however, have testified that the stream descending the mountainside immediately south of Tip No. 1 is perennial and has always carried considerable quantities of water. Apart from a limited amount of run-off available immediately following precipitation from a comparatively small catchment, all this flow originates beneath the tip-complex, and prior to the emplacement of Tip No. 7 emerged at the three points marked 'Issues' on recent Ordnance Survey maps. No surface water is to be observed passing beneath the tip-complex at its upper margins, and so it must be concluded that the perennial flow of this stream originates in one or more springs beneath the spoil.

2.9 A spring was marked 'rising' beneath the site of Tip No. 4 during the 1898 survey and it is reasonable to assume that this was based on actual observation. This position falls on the likely outcrop of the Brithdir Rider mudstone. The spring gives rise to the stream shown on the Ordnance Survey map as passing beneath Tip No. 7 and the extreme toe of Tip No. 3 and emerging at the point marked 'Issues' nearest to Tip No. 3 on the 1956–57 survey. F.E.S. Phillips (Day 13, pp. 638, 655 of the Transcript of the Tribunal Proceedings: see Editor's Note, p. 103) testifies to a spring being covered by Tip No. 4, and both P. Brown (Day 11, p. 515) and W.L. Evans (Day 11, p. 535) refer to a stream emerging at the foot of Tip No. 4, Mr Brown's recollection significantly dating from a time prior to the 1944 slide.

2.10 There is no documentary proof of the existence prior to the disaster of a further spring in the ground covered by Tip No. 7. Nevertheless there is a considerable body of circumstantial evidence to suggest that this was the case. The potential spring-line at the upper limit of the boulder clay runs beneath the tip (see paras. 1.2.1 and 2.4), and water must have been stored up in any open fissures in the Brithdir Sandstone to a level controlled by a spill-over point at this limit.

2.11 In their agreed report on the effects of mining subsidence, Messrs Wardell and Piggott deduce the presence of a 'funnel' or 'corridor' of ground in tension extending north-westwards beneath Tip No. 7 and aligned in the approximate direction of the major joints. It is reasonable to believe that some of these joints have been opened by movements associated with subsidence and have remained open. The 'corridor' passes on the north side of the tip-complex into a broad area, lying beneath the outcrop of the Brithdir Sandstone up-dip, similarly in tension, and where open fissures have been noted. The results of these subsidence movements must be to augment, at least marginally, the percolation of rain-water into the reservoir-rock and to increase substantially the amount of water in storage; in addition the transmissibility along the fissures must also be increased. The tension 'corridor' is flanked to both north-east and south-west by ground believed to be in compression, and here the fissures may well be tight and transmissibility of water low. These modified hydrological characters have been confirmed, at least tentatively, by the tracer tests described in para. 2.4.4 of Appendix I. Brine solution introduced into Borehole L2 in the compression zone north-east of the 'corridor' and 375 ft from the 'new spring' was not proved to re-emerge, while salt similarly introduced into Borehole TR1 in the middle of the tension 'corridor', 570 ft north-west of the 'new spring', issued at the latter point only three hours later, indicating rapid and free flow.

2.12 These investigations confirm that the most likely position of a spill-over spring at the edge of the boulder clay lies beneath Tip No. 7, for it is here that the 'corridor' of open-fissured sandstone connecting with the main storage reservoir to the north-west passes beneath the boulder clay. It is noteworthy that subsidence in the area of the tip-complex was almost complete by 1945.

2.13 Several eye-witnesses have given evidence to the Tribunal that Tip No. 7 did in fact advance to cover a spring lying in the general position deduced above. Thus, for example, H.L. Davies (Day 3, p. 178) observed a stream issuing from the ground later cover by Tip No. 7; Leslie Davies (Day 6, p. 291) agreed that tipping had extended over a spring; and certainly since 1963 water appears to have been emerging almost continuously through the toe of Tip No. 7 (L. Davies, Day 6, pp. 305, 309; G.E. Brown, Day 8, pp. 375–6; Elvet Jones, Day B, p. 426; D.B. Jones, Day 9, p. 479, and Day 10, pp. 496–7; R.L. Short, Day 12, p. 606; T.J. Bennett, Day 12, p. 626). This evidence is both voluminous and credible.

2.14 Further evidence is provided by observations of the discharge of water immediately following the disaster. Flow from the 'new spring' now varies from less than 1000 gallons per hour to more than 20,000 gallons per hour. An initial flow, estimated at as much as 500,000 gallons per hour on the morning of 21st October, must be regarded as utterly abnormal. During the three days it took the flow to decrease to the order of its present flow, it is estimated that some 18½ million gallons of water were drained from the Brithdir Sandstone reservoir. This large discharge must represent an abrupt lowering of the natural water-level within the fissured sandstones by rupture of the boulder clay seal at a point appreciably below the pre-existing natural outlet: this rupture can be directly related to the movement of the disaster-slide (see para. 3.4.B). The new point of emission is believed to have been in the '7-ft cliff' of clay described by Messrs Bowen and Grant, and the waterfall over this face observed by these eye-witnesses confirms that an overflow point existed beneath the tip at a level appreciably higher than the new outburst. Following the heavy rain of 1Bth–19th October the water-level within the fissures of the Brithdir Sandstone must have built up considerably above its normal level.[1] After the 'new spring' outlet had been created there would, for some hours, be enough water within the sandstone to feed both outlets. When P.M. Grant visited the site shortly before midday on 21st October he observed water emerging as a 'waterfall' originating 10 to 15 ft above the point at which tip met the ground. Some short time after 1 p.m. J.J.D. Bowen noted the same waterfall, falling over the 'cliff', the point of issue being the contact between spoil and the ground immediately above the 'cliff'. On the late afternoon of Saturday, 22nd October, Grant records the water as flowing only from the bottom of the 'cliff', the clay-wall of which was 7 ft high. This suggests that within this time there was a drop of water-table of at least 17 to 22 ft in the immediate vicinity of Tip No. 7, and thus that the original spring was at least this much higher than the new outlet. The yield of the latter stabilised itself when the water-table fell to a level compatible with the new position, and this yield and its fluctuations are probably representative of conditions at the earlier pre-disaster spring.

2.15 There seems little doubt, therefore, that a major spring or, more likely, a spring complex, was located at the edge of the boulder clay covering the Brithdir Sandstones in the area concealed by Tip No. 7 in recent years and indeed by earlier tipping. It seems possible that this spring escaped notice by the early Ordnance surveyors because it was located in the stream gulley descending from beneath Tip No. 4. It is significant that the spring beneath Tip No. 4 and that now indicated beneath Tip No. 7 are aligned at 120° azimuth, a direction practically coincident with that of the principal joints (see para. 1.3.3). The relationship may therefore be one of direct association with a line of tectonic weakness affecting successive aquifers.

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[1] Since the disaster, short-term fluctuations of over 60 ft in the level of the water within the Brithdir Sandstone have been measured on the catchment north of the tip-complex (Appendix I, para. 2.5 5).

3. TIP FAILURES

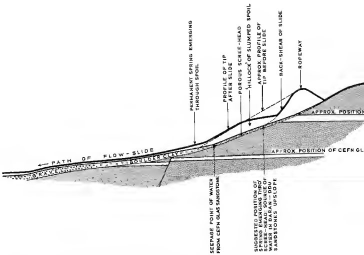
3.1 General

3.1.1 Superficial mass movements of rocks and rock-debris have long been studied by geologists. Such movements range from the extreme case of massive slips of solid rocks to the imperceptible accumulation of hill-wash and head. In all these cases it has long since been recognised that admixed water plays a vital role. In the present context the most pertinent natural phenomena are those grouped by geologists under the name of mud-flows. These are most common in hilly or mountainous terrain where large accumulations of surface debris have been subjected to excessive saturation. The ease of movement is directly related to the proportion of water present: if there is little of this the resultant mud creeps slowly; but with increasing saturation the mixtures may flow rapidly towards the lower ground. Such flows appear to have been especially prevalent in this country in late-glacial conditions, when large masses of unconsolidated and unvegetated debris in places formed thick mantles over the solid rocks. Man-made spoil heaps provide present-day accumulations of debris analogous to these natural ones, and on occasion appear to be subject to the same rules governing their stability.

3.1.2 In the few cases of tip-failure which have given rise to massive and rapidly moving flow-slides, a common mechanism appears to have been operative. It is axiomatic that spoil will only flow in this manner if it contains a considerable proportion of admixed water. This certainly appears to be true of tha slides from Abercynon Colliery Tip and Aberfan Tips Nos. 4 and 7. The accounts set out below are based essentially on examination of features left after the events, and, in the case of the Aberfan Tip No. 7 disaster-slide, take account of data obtained from subsequent site investigation.

3.2 Abercynon Tip Slide of 5th December 1939

3.2.1 Figure 4.5 gives a cross-section of the tip and slide, together with the underlying geology based on the Geological Survey's 6-in. map Glamorgan 28 N.E. revised by field-mapping in 1952, and without the benefit of exploratory investigations such as followed the disaster-slide at Aberfan. The tip is an elongated aerial ropeway edifice approximately 950 yd long extending in a north-west to south-east direction and rising up the slope of the mountain in that direction. After the completion of the original tipping from the ropeway, additional spoil was emplaced on the outward, south-western side of the tip by the provision of chutes from successive tripping points. Towards the south-eastern end of the tip and at a position where rather more spoil had accumulated than elsewhere, a massive failure took place on 5th December 1939. Spoil flowed rapidly down the hillside in a sheet 100 to 150 yd wide leaving a trail of debris up to 40 ft thick strewn on the slope below the original tip. The total length of the flow was nearly 500 yd and its front came to rest in the valley floor only after crossing the River Taff and diverting its course. The material of the flow clearly came from the lower part of the tip, and a large convex 'hillock' of spoil now partly fills the 'crater' out of which the flow emanated. This


PERMANENT SPRING EMERGING THROUGH SPOIL
PROFILE OF TIP AFTER SLIDE
POROUS SCREE-HEAD
'HILLOCK' OF SLUMPED SPOIL
APPROX. PROFILE OF TIP BEFORE SLIDE
BACK-SHEAR OF SLIDE
ROPEWAY
APPROX. POSITION
APPROX. POSITION OF CEFN GL
← PATH OF FLOW-SLIDE
BOULDER CLAY
GRAVEL
SEEPAGE POINT OF WATER FROM CEFN GLAS SANDSTONE
SUGGESTED POSITION OF SPRING EMERGING THRO' SCREE-HEAD: SOURCE OF WATER IN DARAN–DDU SANDSTONES UPSLOPE

4.5 Cross-section showing tip slide from Abercynon Colliery Tip, Cilfynydd Common.

hillock comprises spoil from the upper portion of the tip which has subsided *en masse* into the space formerly occupied by the flow-material.

3.2.2 The hillside on which the tip rests is comprised of the Hughes Beds of the Upper Pennant Measures. The lower part of the Common beneath the tip forms a comparatively gently sloping shelf of ill-drained boulder clay, above which the solid rocks of the Pennant Measures emerge along a pronounced break of slope to form a scarp rising at about 1 in 3. The tip rests almost wholly on the solid rocks mantled by a varying but generally thin layer of sandy scree-head; in the vicinity of the failure the toe just overlapped on to the boulder clay. The recent mapping shows that the Daran-ddu Coal and its associated underlying mudstones crop out beneath the tip throughout its length. The base of the Daran-ddu sandstones overlying the coal thus marks a potential spring line, though the emergent points of springs may lie lower on the slope because of the overlying layer of permeable sandy scree-head. Numerous springs emerge at the upper margin of the boulder clay and there are thus two potential horizons of water-emergence beneath the tip.

3.2.3 Several explanations of the saturation of the flow-material are in vogue. That a lagoon formed behind the tip or between successive lines of tip material is not borne out by Mr W.B. Davies' evidence (Day 51, pp. 2859–60). He saw no sign of such ponding in January 1940, and was told that none had occurred, even in wet weather.

3.2.4 Mr Davies believes that much of the tip was saturated by rain-water following a period of especially heavy rainfall. Observation, however, suggests that the amount of rain that passes into a colliery spoil tip by direct percolation is not large. The slopes of such tips are normally steep and most water runs off them, forming deep runnels, such as those well developed on the Abercynon tip. Tips show scarcely any weathering of spoil beneath a thin surface skin, and this provides further evidence of restricted permeability. If rain-water were indeed a source of real danger, many other colliery tips in South Wales would have collapsed long since.

3.2.5 Springs provide a more credible explanation for the saturation of the spoil. The existence of the Daren-ddu mudstones beneath the tip makes such an explanation likely, for their outcrop is a potential spring-line, the position of which is shown in Figure 4.5. The Daren-ddu sandstones above the tip are virtually bare to the surface and fissures resulting from mining subsidence are also to be seen. During the period of heavy rainfall in the weeks preceding the slide, water would percolate freely into the sandstone and the yield of any springs emerging at or just below its base would increase significantly.

3.2.6 The upper limit of the boulder clay is a second potential spring-line beneath the tip, but its position appears to lie too near to the original toe of the tip to saturate appreciable quantities of the spoil. It is perhaps significant that a permanent spring can now be seen emerging through the spoil near the junction of the flow-slide and the subsided 'hillock' of spoil, and this sends a small stream down-slope through the path of the flow.

3.2.7 There are no accounts which suggest that the slide was associated in its aftermath with any observable free flow of water, nor is there any channelling of the slide to support such a contention.

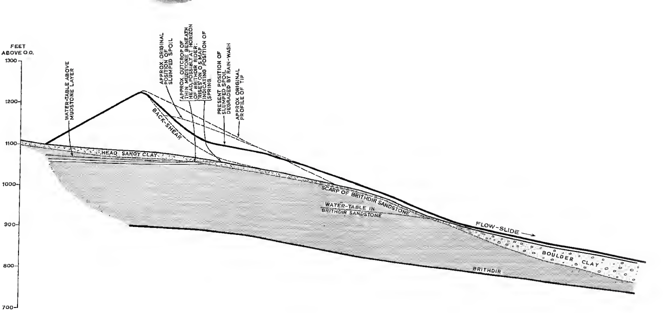
3.3 **Aberfan Tip No. 4 Slide**

3.3.1 A cross-section of this tip after failure is given in Figure 4.6. The tip was emplaced on Pennant sandstones lying between the Brithdir and the Cefn Glas mudstone complex. The Brithdir Rider Coal, known on the western side of the Mynydd Merthyr, is not developed in the area of the tips, but recent borings have suggested the presence of a continuous, though thin, layer of mudstones at its horizon, and this probably crops out beneath the tip, giving rise to the spring marked on the Ordnance Survey map (see para. 2.9). The solid rocks are covered by a substantial mantle of head deposits.

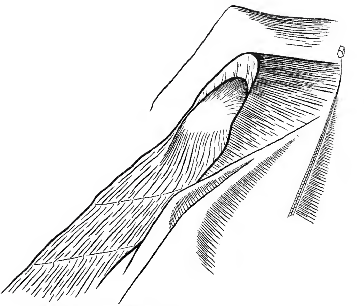
3.3.2 In the late autumn of 1944, following some two months of very wet weather, a flow-slide poured down the hillside for a distance of about 500 yd. Throughout much of its lower course the slide formed an elongated tongue 20 to 50 yd wide and about 10 to 15 ft high; in its upper part, where it emerged from the tip, the slide had a width of approximately 100 yd. The margin of the slide throughout its length was characterised by slopes apparently conforming to angle of rest, and the visible material consisted of coarse angular blocks of typical run-of-mine spoil. Evidence has been presented by T.J. Davies (Day 17, pp. 888, 893) suggesting that at least along some part of its path the moving mass gouged about 4 ft into the underlying sub-soil.

3.3.3 It has been suggested that this slide was a 'dry' one. It is, however, inconceivable that such material could flow so freely over such a long distance unless it was in fact heavily water-laden.

3.3.4 It is therefore postulated that, following exceptionally heavy rain, the yield of the buried spring increased to such an extent that a considerable volume of spoil in the lower part of the tip became saturated to failure-point. This wet mass burst out as a flow-slide, gaining perhaps a little acceleration as it passed over the steeper slope of the Brithdir Sandstone scarp, and the overlying relatively dry tip subsided into the resultant space. Weathering over the years since 1944 has


FEET ABOVE O.D.
1300
1200
1100
1000
900
800
700
WATER-TABLE ABOVE MUDSTONE LAYER
APPROX ORIGINAL POSITION OF SLUMPED SPOIL
APPROX OUTCROP OF THIN MUDSTONE BENEATH HEAD, POSSIBLY AT HORIZON OF BRITHDIR RIDER. 'RISES' ON O.S MAP INDICATING POSITION OF SPRING
PRESENT POSITION OF SLUMPED SPOIL DEGRADED BY RAIN-WASH
APPROX ORIGINAL PROFILE OF TIP
BACK-SHEAR
HEAD SANDY CLAY
SCARP OF BRITHDIR SANDSTONE
WATER-TABLE IN BRITHDIR SANDSTONE
FLOW-SLIDE
BOULDER CLAY
BRITHDIR

4.6 Cross-section showing tip slide from Aberfan Tip No. 4.



4.7 Sketch diagram illustrating the failure of Aberfan Tip No. 4.

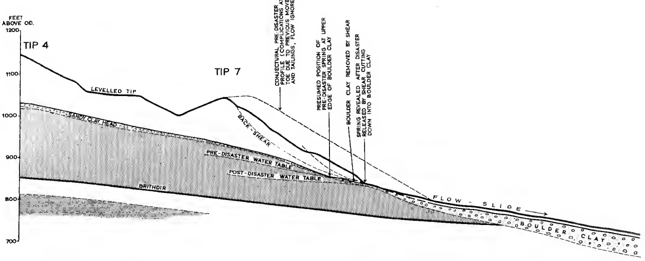
softened the contours of the subsided mass and its underlying 'crater' as is shown in Figure 4.6. The sketch of Figure 4.7 attempts to illustrate the appearance of the tip immediately after the slide.

3.3.5 Consideration of the mining evidence has led to the conclusion that subsidence movements, active in the area at the time of the slide, may have been a factor in triggering the failure. It should be realized, however, that no matter how severe such ground movements might have been, the spoil could not have moved such a great distance unless it had been already saturated. Subsidence activity under these conditions can only advance the moment of failure.

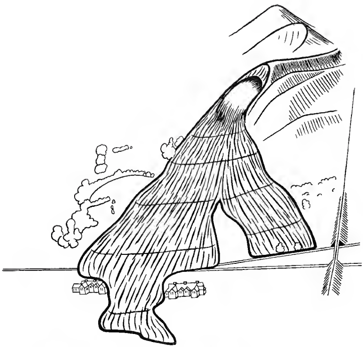
3.4 **Aberfan Tip No. 7 and the Disaster of 21st October 1966**

3.4.1 Tip No. 7 was constructed on ground formed by the Brithdir Sandstone, and in its later stages extended down-slope on to the upper part of the boulder clay tongue above Hafod-tanglwys-uchaf (see Figure 4.8). A layer of stony sandy clay head covers the solid rocks and extends on to the boulder clay. As described above (para. 2.10), a spring is believed to have been located at the upper margin of the boulder clay in the vicinity of the stream-course marked on the old Ordnance Survey maps.

3.4.2 Tip No. 7 was started in April 1958 and by about 1962 tipping had already extended over the ground occupied by the presumed spring. Soon after this, evidence of instability began to appear and persists almost continuously until the disaster. The air photograph of May 1963 (see Fairey Surveys, Fig. 6, Ed.) shows a slight depression in the lower part of the point of the tip, and by September 1963 this


FEET ABOVE OD.
1200
1100
1000
900
800
700
TIP 4
TIP 7
LEVELLED TIP
SANDY CLAY HEAD
BACK - SHEAR
PRE-DISASTER WATER TABLE
POST-DISASTER WATER TABLE
BRITHDIR
CONJECTURAL PRE DISASTER PROFILE (COMPLICATIONS AT TOE DUE TO PREVIOUS MOVEMENTS AND TAILINGS, FLOW IGNORED)
PRESUMED POSITION OF PRE-DISASTER SPRING AT UPPER EDGE OF BOULDER CLAY
BOULDER CLAY REMOVED BY SHEAR
SPRING REVEALED AFTER DISASTER RELEASED BY SHEAR CUTTING DOWN INTO BOULDER CLAY
FLOW - SLIDE
BOULDER CLAY

4.8 Cross-section showing disaster slide of October 21, 1966 from Aberfan Tip No. 7.



4.9 Sketch diagram showing the first phase of Aberfan Tip No. 7 failure.

had developed into a definite though small crater-like hole. In November 1963 a major incident occurred, the exact details of which are not entirely clear. It is apparent, however, that a flow of wet material took place from within the base of the toe and was accompanied by a collapse of the overlying material apparently along a shear which extended upwards through the tip to the approximate position of the crane (see T.H. Davies, Day 12, pp. 587–8). The spring-water which presumably caused this slide was observed by several of the workmen and its flow produced a back-sapping hole in the toe of the remaining part of the tip, in almost the same position as that observed in September 1963 (see G.E. Brown, Day 8, p. 400; E.C. Jones, Day 8, pp. 426, 432, 459; D.B. Jones, Day 10, pp. 496–7; R.L. Short, Day 12, p. 606; T.J. Bennett, Day 12, p. 626). By June 1965 this hole had been almost filled in. It may have been recreated during the winter of 1965–66 (see photograph D.8) but by October 1966 its site was apparently no longer visible to surface observation (H.L. Davies, Day 4, p. 216). Nevertheless, constant minor subsidences were taking place higher in the tip and they appear to have been caused by activation along the same surface of shear-weakness.

3.4.4 On 21st October 1966 these movements culminated in a catastrophic collapse of the tip. Subsidences of as much as 20 ft had already occurred along the face in the hour or two before complete failure, which took place at about 9.17 a.m. At that time a large volume of soaking tip-debris swept with great rapidity down the hillside and overwhelmed part of the school buildings and numerous adjacent houses. The accounts of the various eye-witnesses are difficult to collate, and the exact sequence of events remains a matter for some conjecture. Nevertheless, it appears reasonably certain that when the slide material first arrived in the vicinity of the schools it contained no free water, though once movement ceased water trickled from it freely (Colin Jones, Day 3, p. 123; K.J. Davies, Day 3, pp. 128, 134). It also seems clear that, closely following the release of this 'porridge'-like material, a large quantity of water swept down the hillside, eroding, in the upper part of its course, a channel through the spoil and depositing its load lower down the slope. The time interval between the two phases cannot have been great: the initial collapse witnessed by the workmen at the top of the tip evidently produced the slide which demolished the school; the main release of water appears to have been witnessed by Leslie Davies (Day 5, pp. 269–70) when he reached Tip No. 1 not more than a few minutes after being called by G.E. Brown.

3.4.5 The disaster-slide of Tip No. 7 differs, therefore, from the failures on Abercynon and No. 4 tips described above in the emission of large quantities of free water immediately after the slide had taken place. In its first phase, however, it seems closely analogous to those events.

3.4.6 The spring at the upper margin of the boulder clay is presumed to have increased its yield following the heavy rainfall of 18th–19th October, causing the water-table to rise within the tip to such an extent that outward flow of the saturated spoil ensued. It was this flow of spoil which produced the main disaster. Collapse of overlying relatively dry spoil followed, producing a temporary situation as envisaged in Figure 4.9. Much of this collapsed 'dry' spoil was quickly removed through back-sapping by the subsequent flow of water, but immediate post-disaster photographs show quite clearly that a significant part of it remained in place until remedial excavations were carried out. Its top can be recognised on photographs D.15 and D.18, particularly above the southern side of the spring 'crater', as a sloping 'terrace' about half-way up the collapse-face.

3.4.7 It has already been stated (see para. 2.14) that the flow of the 'new spring' revealed after the disaster was wholly abnormal, and remained so for about three days, implying that its outlet was situated perhaps an appreciable distance below the former point of emission. Investigations carried out by Professor Bishop have revealed evidence which satisfactorily explains the rupture of the boulder clay to produce the new outlet for the water held within the Brithdir Sandstone.

3.4.8 The somewhat diagrammatised Figure 4.10 shows a shear[1] passing down from tip through soil and into the boulder clay at the change of slope which marks the latter's up-hill limit and effectively weakening the clay-seal at this point. As stated above (para. 2.14), the break-out point is presumed to be at the '7-ft cliff' described by Messrs Bowen and Grant. This 'cliff'-face is unlikely to form part of the shear, for it is far too steep and is limited only to the immediate vicinity of the 'new spring'; it is very similar in form and size to the 'cliff' formed by the Abercwmboi outburst of December 1960 (see para. 4.2), and compares with the sites of many water-bursts in high moorland areas.

3.4.9 The spring from Tip No. 4 feeding the stream emerging beneath the lower complex has continued to flow since the disaster, and the water probably follows its old course just to the north of the 'new spring' culvert. After rain it appears to spill over its banks beneath the

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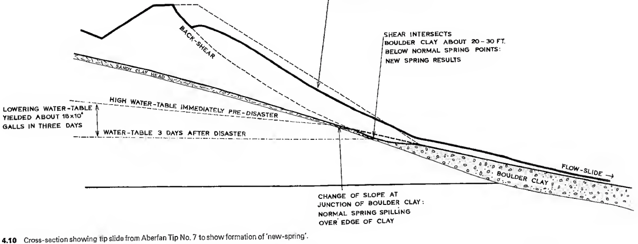
[1] The shear surface when seen was exposed over a length of about 70 ft, and showed abundant movement striae on it. The direction of the striae, namely 106° to 132° azimuth, proved to be much as would be expected from the general observations concerning the mass movement of the tip. An approximately cuboidal boulder of colliery waste composed essentially of hard sandy siltstone showed well-marked scratches on one of its upper surfaces; this surface evidently coincided with that of the shear. It seems unlikely that these scratches could have been produced by any agency other than movement within the tip.


PROFILE OF SLUMPED SPOIL IMMEDIATELY PRIOR TO EMERGENCE OF NEW SPRING
BACK-SHEAR
SHEAR INTERSECTS BOULDER CLAY ABOUT 20 - 30 FT. BELOW NORMAL SPRING POINTS: NEW SPRING RESULTS
SANDY CLAY HEAD
LOWERING WATER-TABLE YIELDED ABOUT 18x10^4 GALLS IN THREE DAYS
HIGH WATER-TABLE IMMEDIATELY PRE-DISASTER
WATER-TABLE 3 DAYS AFTER DISASTER
FLOW-SLIDE →
BOULDER CLAY
CHANGE OF SLOPE AT JUNCTION OF BOULDER CLAY: NORMAL SPRING SPILLING OVER EDGE OF CLAY

4.10 Cross-section showing tip slide from Aberfan Tip No. 7 to show formation of 'new-spring'.

tip, giving rise to seepages through spoil in the area around and above the culvert.

3.4.10 By analogy with the Abercwmboi outburst (see below), the 'new spring', during its early stages of great flow, probably scoured the ground in its path immediately below the 'cliff'. This erosion together with a certain amount of excavation made during the emplacement of the culvert, has enabled the spring to migrate even further downhill than the point of original outburst. The direction of this migration is clearly shown by the upper course of the culvert; this is parallel to that of the principal joints, showing that the water is flowing directly from one major fissure-system. Variations in rainfall and consequent changes in the height of the water-table in the sandstones behind the spring are now reflected by upward and downward movement of the spring position within the culvert.

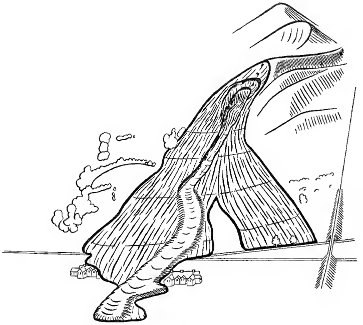
3.4.11 The large flow of water observed on 21st October demands the presence of a correspondingly large fissure-system behind the site of emission. Two boreholes have been drilled to prove the existence of these fissures. These have provided confirmatory evidence in the form of records of gaps and voids noted by the driller.

3.4.12 The effect of the torrent produced by the release of the new spring is best shown by photographs D.15 and D.16 (D.16 is Plate 7 of the Report of the Tribunal, Ed.). The results are confined to only a small central strip within the main sheet of the disaster-slide, and have been clearly superimposed on it. Immediately around the source of the spring a considerable part of the collapsed spoil has been sapped and washed downhill by the stream. In the upper and steeper part of its course, the debris-laden stream has eroded a deep channel into the spoil of the slide. About 200 yd above the railway embankment, active erosion ceased and the stream, by virtue of its contained load and the slacker gradient on to which it here passed, became a highly mobile mud-flow, the main role of which was to deposit further spoil upon that already produced by the disaster-flow. During the morning of 21st October and before the main stream of water had been diverted, it was this flow that remained intermittently mobile in the devastated area, and was probably responsible for the several surges noted by eye-witnesses. Any local effects produced by the fractured water main also appear to have been swamped by the mud-flow before photographs were taken. Figure 4.11 illustrates the superposition of the effects of the water-burst on the original slide.

3.4.13 The tipping of washery tailings on Tip No. 7 has been a live issue at the Inquiry. The role played by this type of spoil in the disaster-failure is a matter for the soil mechanics experts, but it is pertinent to point out that the failure of Tip No. 4, at least, took place in the absence of such material. The almost constant run of tailings from the surface of the tip, dating from a time virtually coincident with the passage of the tip itself over the spring, appears, however, to have confused observation and concealed the evidence of developing instability within the main mass of Tip No. 7.

4. CRAIG ABERCWMBOI OUTBURST OF WATER

4.1 The outburst of 4th December 1960, on the mountainside above Abercwmboi took place following one of the periods of heaviest rainfall recorded. It was sited on the horizon of the No. 1 Rhondda Rider Seam, workings of which were extensive up to the Gadlys Fault, and reached almost to the crop of the seam in the neighbourhood. The burst took



4.11 Sketch diagram showing subsequent modification of disaster-slide by flow from 'new spring'.

place on a small fault, the local effect of which would be to seal the old workings and the 20-ft sandstone forming the roof of the seam on the down-dip side. It is reasonable to believe that the water was associated with the workings and the roof-sandstone—a conclusion which gains support from the initial discolouration of the water noted by witnesses. Small springs continue to flow at the site and one such spring is indicated on the Ordnance map. Further springs also occur along the line of outcrop of the coal.

4.2 The back of the cavity torn in the scree-head at Abercwmboi is similar in general form to the 'cliff' which apparently marks the site of the original outburst of the 'new spring' at Aberfan. In both cases the height of the 'cliff'-face is similar and in the case of Abercwmboi it is said to have taken about 15 minutes to form. At Abercwmboi about 2520 cubic yards of debris are estimated to have been eroded from the cavity.

5. RECOMMENDATIONS REGARDING FUTURE CONTROL OF SAFETY ON TIPS

Two principal disciplines are involved in the consideration of safety and stability of tips—that of civil engineering (with its background of soil mechanics) and that of geology. With regard to the control of existing tips the civil engineer is the more important, though he would need to know the basic geological and hydrological facts and to call in a geologist where the interpretation of these was not obvious. In the case of the selection of sites for tipping, however, the geologist's role is probably the more important. While the load-bearing properties of the foundation materials are important in all cases, it must be appreciated that catastrophic failure of the type under consideration is invariably associated with springs. The location of springs and potential spring-lines is an aspect of hydrogeology which demands an experience of field geology normally outside the orbit of the civil engineer. Spring emergence is often ephemeral, and, in the absence of precise observation spread over several years, only the geologist should be expected to interpret the potentialities of the ground-water pattern.

6. CONCLUSIONS REGARDING NO. 7 DISASTER SLIDE

6.1 Tip No. 7 was extended to cover a spring draining the Brithdir Sandstone.

6.2 Following heavy rain on 18th–19th October, and a delay in accordance with the normal ground-water response for the area (see Appendix I, para. 2.6.4), the yield of the spring increased and saturated the lower part of the tip sufficiently to make it flow. This initial flow was the cause of the main disaster.

6.3 The upper part of the tip subsided into the space vacated by the flow-spoil.

6.4 The mass movement of spoil caused rupture of the boulder clay holding back the water in the Brithdir Sandstone at a point some distance below the pre-existing spring. The resultant abnormal flow of water under pressure took three days to subside and caused a secondary very mobile mud-flow which produced further, though comparatively minor, damage in the destruction area. The area affected by this flow of mud was restricted to a comparatively small part of the ground covered by the disaster-slide.

Note. The surface profiles of Figures 4.5, 4.6 and 4.8 are based on levels taken from documents provided by the Tribunal. The geological interpretation is qualitative rather than quantitative and is intended solely to aid the reading of the text. Figure 4.10 is essentially diagrammatic.

APPENDIX 1

GROUND-WATER CONDITIONS IN THE PENNANT SANDSTONE

by

D. A. GRAY BSc PAIWE[1]

1. INTRODUCTION

1.1 A general statement of the hydrogeology of the Aberfan area has been included in the report by Dr A.W. Woodland, Assistant Director of the Institute of Geological Sciences. In particular, Dr Woodland examines the evidence concerning the possible presence of a spring or spring complex beneath the tips prior to the commencement of tipping. Such evidence is not reconsidered in the present report which deals with measurements relative to the ground-water conditions in the Drift deposits and in the Pennant Sandstone in the vicinity of the tips. It is based largely on evidence provided to the Institute of Geological Sciences by the staff of other organisations and, with the few exceptions detailed below, measurements have not been verified by the Institute's staff. Few of the measurements, or the frequency with which they are made, were designed specifically for hydrogeological purposes.

1.2 The measurements of water-levels in the piezometers were obtained as part of the soil mechanics programme. The stream-flow measurements used in the report were provided by the National Coal Board. The Meteorological Office supplied daily rainfall data for Mountain Ash and these have been used in the present report.

2. GROUND-WATER HYDROLOGY

2.1 The occurrence of ground water

2.1.1 The distribution in the area of the Pennant Sandstone and of the overlying Drift deposits has been described elsewhere. Rain and other forms of precipitation falling on these deposits is disposed of in one of three ways: (i) by evaporation and transpiration, (ii) by surface run-off, and (iii) by infiltration into the rocks underlying the soil layer. Water which infiltrates into the saturated zone of the rocks is termed ground water. This moves through the pore spaces or fissures in the strata in a direction and at a speed controlled by the character of the rocks and by the prevailing hydraulic gradient. After passage through the strata, ground water is discharged at a spring or a line of seepage. The present report is concerned with infiltration; with the relationship between surface run-off and infiltration; with the passage of ground water through the Pennant; and with the discharge of ground water from the Pennant and the Drift deposits.

2.1.2 During 1966 ground-water levels in the principal water-bearing rocks of England and Wales were high. This position resulted largely from heavy infiltration in December 1965 and early 1966, followed by a relatively wet summer. The Meteorological Office data indicate that the same general condition applies at Aberfan. With the catchment in a saturated condition and no soil moisture deficit, the rate of infiltration in October 1966 is likely to have been rapid.

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[1] Water Department, Institute of Geological Sciences.

2.2 **The Drift deposits**

2.2.1 For present purposes the Drift deposits have been considered as two formations—*Boulder Clay* and *Head*. The Boulder Clay is important in that it blankets the deposits beneath it and, being relatively impermeable, confines the water in underlying deposits. 'Head' deposits, consisting of weathered debris derived from the solid strata (sandstones and mudstones), mask most of the outcrop of the Pennant Sandstone in the catchment areas of the numerous springs, seepages and streams which drain the area.

2.2.2 Both of the deposits are porous and are characterised by variable permeability. In general, the permeability of the Boulder Clay should be lower than that of the Head, but locally, where the clay content of the Head is high, this may not be so. The infiltration capacity of the Head will be lowered by the presence of a high clay content, and in areas where this occurs infiltration will be inhibited or eliminated and surface run-off will result. Such run-off, as well as that rejected as spring-flow and seepages from other strata, may be absorbed into the Head elsewhere where the infiltration capacity is higher or mine-subsidence fissures break surface.

2.3 **The Pennant Sandstone**

2.3.1 Being well cemented, the unweathered Pennant sandstones have a negligible porosity but they are able to both store and transmit water in joints which are commonly strongly developed in them. Infiltrating water entering these rocks from the overlying Head changes its method and velocity of flow from slow intergranular movement in the Head to relatively rapid fissure flow. Infiltration drains down through open joints until it reaches a saturated zone in the sandstone whence it flows laterally under the action of the prevailing hydraulic gradient, until it is discharged to the surface at springs or seepages. The spring thought to underlie Tip No. 7 before the slip on 21st October is one such outlet. Its location is thought to have been determined by the presence of Boulder Clay resting on the Pennant Sandstone. Whether or not discharge from the spring took place into the tip material through Head resting on the Boulder Clay or directly from the Pennant is not known.

2.3.2 Where the Pennant sandstones have been placed in tension, either due to mining activities or to their natural dispositions on the valley sides, joints and fissures in them are likely to be more open than elsewhere. The ability of the strata to store and transmit water will be correspondingly higher in such areas.

2.4 **Effects of mining subsidence**

2.4.1 The agreed report on subsidence effects provided by Messrs Wardell and Piggott is the origin of the data considered below. The effects of the mining upon the hydrogeology in those areas subjected to lateral tensional displacement are three-fold. Firstly, ground-water recharge through subsidence fissures, which have extended upwards from the mine workings to reach the ground surface, has been increased by permitting surface run-off to gain access to underlying strata. Secondly, enlargement of pre-existing fissures underground will have increased the storage capacity of the Pennant Sandstone. Thirdly, the same tensional effects will have increased the capacity of the formation to transmit water. The latter two effects are unlikely to have altered the hydrogeological significance of the mudstone beds.

2.4.2 These three processes, either alone or in combination, may account for the enlarged ground-water catchment for the central complex of streams referred to below. In particular, lateral tensional displacement in the narrow zone of tension orientated approximately north-west to south-east beneath Tip No. 7, could have been a significant factor in increasing the underground catchment area to the stream now issuing from the culvert at the site of Tip No. 7.

2.4.3 Conversely, the zone of compression bounding the western side of that zone of tension may possibly be associated with the allegedly 'dry' Borehole R3 (see Figure 4.2 Ed.). There may be some doubt as to the significance of this effect, however, because a piezometer installed in Borehole R2 in the Brithdir Sandstone (37 ft above the Brithdir Coal) indicated dry conditions between 23rd November 1966, when it was installed, and 7th January 1967, when a trace of water was recorded; subsequently, water has been present in the piezometer.

2.4.4 Tracers injected on 22nd February 1967 into Borehole L2, which is said to be located in a zone of compression, had not been recovered after 45 hours at any of five sampling points. In particular, they had not been recovered from the spring at the foot of Tip No. 7 at a distance of 375 ft to the south-east of the point of injection. A second experiment was carried out on 8th March 1967 with tracers injected into Borehole TR1, located in the narrow zone of tension beneath Tip No. 7. After three hours a change in the chemical quality of water sampled from Borehole P/IV-6 in the culvert indicated that tracer was being discharged from the borehole. One hour later a similar indication was observed at a second sampling point at ground level in the culvert. Each of these sampling points is approximately 560 ft from the point of injection. The equivalent horizontal velocity, under the natural hydraulic gradient of 1 in 28 which existed prior to and after the injection of the tracer, was equal to approximately 3 ft per minute so far as the borehole was concerned and to about 2 ft per minute for the ground level sample. The inaccuracies inherent in tracer techniques do not allow the determination of a more specific velocity. Three other factors are relevant to these experiments. Firstly, injecting the tracer raised the water level in Borehole TR1 by 88 ft during the hour-long period of injection. The water level had returned to its original depth within 40 minutes of the completion of injection. Secondly, the exact position of Borehole TR1 is not available to the Institute at the time of the preparation of this report, and the estimate of 560 ft for the distance between point of injection and points of sampling may be a few feet in error. Thirdly, the quantity of tracer in solution in recovered samples is stated by the National Coal Board to indicate that a quantity of tracer in excess of 500 lb had passed the sampling points. During the first experiment 336 lb of tracer were injected (22nd February) and 2240 lb during the second exercise (8th March). Thus it is concluded that the tracer identified on 8th March relates to the injection of the larger quantity on the same day and has no relevance to the first and smaller injection.

2.4.5 It appears that the boundaries between zones of tensile and compressive strains cannot be disragarded as potential hydraulic boundaries, or at least as possible hydraulic discontinuities.

2.5 Water-level measurements

2.5.1 The measurements obtained from piezometers installed since the slip in October 1966 fall into two main groups: (i) those from instruments installed in the Drift or just in the sandstone, and (ii) from those placed well into the sandstone. The first group is characterised by slow changes in head of a low amplitude (range less than 10 ft) and is clearly differentiated from the second group in which changes in head are rapid and of a higher order of magnitude (range 10 ft or more). The differentials between these groups probably reflect intergranular flow in group (i), with subordinate fissure flow in the talus and weathered Pennant Sandstone; and exclusive fissure flow in group (ii).

2.5.2 The piezometers for which readings extending over a period of two weeks or more have been provided to I.G.S. (at 25th February 1967) are as follows:

C4, E4, F3, F6, HG1, K1, K2, K3, K4, K9, K10
K11, K12, L3, L7, L8, R2, R4, R5, R6, R7, R8.

Their distribution into groups is as follows:

Group (i) C4, E4, F3, F6, K1, K2, K3, K4, K9
K10, K11, K12, L7, L8 (L7 and L8 dry).
Group (ii) In the Pennant Sandstone: HG1, HG2, L3, R2, R4, R5, R6, R7, R8.

2.5.3 Piezometer C4 behaved anomalously in that it appeared to indicate a rapid fall in water-level between 1st and 13th February 1967, after which date it has remained 'dry'; the possibility of an ineffective installation cannot be eliminated.

2.5.4 In addition, an automatic water-level recorder has been installed in Borehole 8A which is lined with slotted casing. Some measurements of the pressure head in an inclined borehole drilled at the head of the culvert have been made but, owing to the inclination, the readings have not been considered because they represent a resultant pressure dissimilar from any others on the site.

2.5.5 In fissured strata not subjected to mine subsidence, it is the normal expectation that the amplitude of fluctuations will be less in the low ground than that observed on the higher ground. Such is the case with Borehole R5, in the low ground near the cemetery, and R6 on the higher ground north of the tips. The rise in water level in R5 between 16th and 21st February amounted to 12 ft 11 in., to compare with 60 ft 3 in. in R6. During the same period the water level at R8, even higher on the catchment than R6 but installed at a higher stratigraphical level, is recorded as having risen by 62 ft 0½ in.

2.5.6 Prior to the main slip on 21st October, Drift deposits of varying thickness are thought to have separated the Pennant Sandstone from the tip material. Thus any pressure variations on the base of the tip which resulted from variations in the head of water in the Pennant Sandstone would, of necessity, have had to be transmitted from the Pennant Sandstone through the Drift. Although the measurements made since the slip occurred have not reproduced the exact conditions prior to the slip, the absence of large or rapid variations in group (i) installations tends to suggest that any major changes in the hydrostatic head within the Drift deposits beneath the tip were generated elsewhere than in the Pennant Sandstone. Should it be shown that beneath some part of the tip Drift was absent, this conclusion would be invalid, for the rapid and considerable changes of head recorded in the Pennant Sandstone could then have been transmitted directly to the spoil.

2.5.7 It is unrealistic to assume that, during the short period of observation since the piezometers were installed, the water level in the Pennant Sandstone has reached its highest-ever elevation. The highest so far recorded has been in R8 where it is reported to have reached a level of 1102·8 ft above Ordnance datum on 21st February 1967 (recorded as 122 ft 10½ in. below datum). The maximum head which could have been exerted on the base of the Drift beneath the tip as a result of ground water in the Pennant Sandstone would be equal to the difference in elevation between the 'issue' beneath the tip at approximately 840 ft O.D. and the highest water level in the catchment, *less* the head-loss due to frictional resistance to flow through the intervening strata. The maximum difference so far recorded amounts to 1102–840 ft, i.e. 262 ft *less* an unknown head-loss. Reliable estimates of the head-loss cannot be made in the disturbed hydrogeological conditions now existing in the area. Accordingly extrapolation back to the time when Tip No. 7 was in place would be subjective in the extreme, and would be unlikely to result in a meaningful estimate of the pressure exerted by ground water on the base of the Drift below the tip.

2.5.8 There seems little doubt that it was ground water which issued from the tip at a high but decreasing rate of flow after the slip took place. It appears probable, however, that it was drained from the Pennant Sandstone by the 'opening' of a point of issue at a lower level than was present prior to the slip.

2.6 **Stream hydrographs**

2.6.1 The stream hydrographs supplied by the National Coal Board have been analysed in order to determine the lapsed time interval between the occurrence of heavy rain and the response of stream flow. The rainfall data employed were those supplied by the Meteorological Office for the rain gauge at Mountain Ash.

2.6.2 Rainfall measurements have been compared with stream flows observed at each gauging point at differing and varying time intervals. Comparison of the distribution of rainfall throughout each 24-hour period with a continuous record of stream flow is clearly desirable but impossible with the data available.

2.6.3 The lapsed time between the occurrence of rainfall allocated to a particular date and the onset of high corresponding stream flow has been estimated for dates on which rainfall followed a markedly dry spell, or on which high flow can be related with reasonable certainty to rainfall in the preceding period. In order to avoid spurious indications of accuracy, the time intervals have been classified only in terms of days—less than one day, one day, one to two days, two days, and more than two days. Results are shown in Table 1 below.

2.6.4. It can be concluded tentatively that the lapsed time for V6, under post-slip conditions, amounts to two days or more, compared with one day or less for V3, V4 and V5. The increased lapsed time at V6, which provides a proportion of the water measured at V3, accounts to some extent for extended periods of high flows at V3. Moreover, the flow from V3 is sustained at a higher rate for a longer time than those at V4 or V5 because the ground-water component is greater.

2.6.5 Whether the longer lapsed time applied at V6 prior to the slip, or whether the new conditions have yet to attain equilibrium, is not known. There is some indication, however, that the same condition existed prior to the slip because there was heavy rain on 19th October and the slip took place two days later on 21st October.

2.6.6 An analysis of the flow characteristics has been made of the stream hydrograph for V3. During the period analysed, 31st October 1965 to 25th December 1965, the ground-water component amounts to about 75 per cent. The percentage appears high for a drift-covered area of Pennant Sandstone and can be interpreted as implying that the natural conditions have been seriously disturbed. It is probable that the ground-water catchments of these streams differ markedly from the

Table 1

Lapsed times between rainfall and increases in stream flow

Rainfall	V3* flow	Lapsed time at V3* days	V4* flow	Lapsed time at V4* days	V5* flow	Lapsed time at V5* days	V6* flow	Lapsed time at V6* days
4.11.66	5.11.66	Less than 1						
29.11.66	30.11.66	1	30.11.66	1	30.11.66	1	3 12.66	
1.12.66			1.12.66	Less than 1	?1 12.66	?Less than 1		
9.12.66	9.12.66	Less than 1	10.12.66	1	10.12.66	1	11.12.66	More than 2
11.12 66	11.12.66	Less than 1						
12.12.66	13.12.66		12.12.66	1	13.12.66	1		
14.12.66	15 12.66	1						
15.12.66	16.12.66	1	16.12.66	1	16.12.66	1		
23.12.66	24.12.66	1						
28.12.66			29.12.66	1	29.12 66	1		
30.12.66	31.12.66	1	31.12.66	1	31.12.66	1	1.1.67	2

*The flows allocated to V3, V4, V5 and V6 are those measured by the N.C.B. as follows:

V3—all drainage from the 'Central Complex'

V4—South Stream

V5—'Nant Maen'

V6—that part of the flow measured at V3 which emanates from the 'New Spring' at the head of the culvert and which is separately measured.

surface-water catchments. It can also be inferred, with some reservations, that the underground catchment for the central complex has been enlarged either naturally or artificially, probably at the expense of the adjoining 'Nant-y-Maen' and 'South' streams.

3. **Conclusions**

3.1 Joints in the Pennant sandstones are sufficiently open to store and transmit ground water in appreciable quantities. Mine subsidence, which is reported to have ceased before the slip of 21st October 1966, contributed to the enlargement of pre-existing natural fissures and where these reached the surface, drainage into the Pennant Sandstone was facilitated. Not only was the rate of infiltration increased, but the underground catchment drained by the streams in the central complex appears to have been enlarged.

3.2 Until otherwise proven, boundaries between zones of tensile and compressive strains should be regarded as potential hydraulic discontinuities.

3.3 Rapid and considerable fluctuations have been recorded in the level of the ground water in the Pennant Sandstone. Analogous fluctuations measured in the Drift deposits during comparable periods have taken place far more slowly and were significantly lower in magnitude. No measurements known to the Institute and made since the slip took place, indicate that the large variations in the pressure-head of the ground water in the Pennant Sandstone have been detected in the Drift deposits. Equilibrium conditions may not yet have been attained in drainage adjustments which followed the creation at the time of the slip, of a new outlet for ground water. Thus, post-slip measurements may not yet be fully indicative of the pre-slip conditions. So far as such measurements are meaningful, however, they appear to indicate that the Drift deposits do not transmit short-term ground water fluctuations of high amplitude. An increase in the ground-water pressure in the Pennant Sandstone following increased infiltration into the outcrop of the formation, would have led to an increased rate of discharge into the overlying Drift deposits and hence into the tip. The higher pressure would not, however, have been transmitted rapidly or fully except in areas where Drift deposits are absent.

3.4 The large volume of water which issued from Tip No. 7 and from the ground surface beneath the tip virtually at the same time as the occurrence of the slip, was ground water derived from the Pennant Sandstone. The cause of its release can be attributed to a combination of failure of the overlying Drift deposits and to scour produced by the slip.

3.5 The lapsed time interval between the occurrence of heavy rain and an increase in flow in the stream leading from the culvert at Tip No. 7 has amounted, in post-slip conditions, to two days or more. This compares with one day or less for the Nant-y-Maen to the north of the tips and the 'South' stream to the south of the central complex.

3.6 The ground-water components of the streams draining the hillside appear high for a drift-covered area of Pennant Sandstone; probably because the ground-water catchments have been enlarged and infiltration increased by mining subsidence.

Geological Report on the Tipping Site and its Environs at Merthyr Vale and Aberfan

by **Leslie Rowsell Moore** BSc PhD DSc CEng MIMinE FGS*

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*The main conclusions from the Appendices are contained in the Report, and the five Appendices have not been reproduced here. They can be seen, with other documents presented to the Tribunal, at the Treasury Solicitor's Office, 3 Central buildings, Matthew Parker Street, London SW1, by prior appointment.

Introduction and synopsis

The Report describes the geology and hydrology of the site of the catastrophy at Aberfan and is based primarily on the published Geological Survey maps of the area. The geological maps and sections accompanying the Report include a great deal of additional actual evidence which has been obtained by field work, borehole and geophysical investigations.

The Report demonstrates the coincidence of a set of geological factors, each of which, in itself, is not exceptional, but which collectively create a particularly critical geological environment. These are:

(i) The presence beneath the tipping area of an embayment or side valley in the steeply sloping side of the main Taff Valley.

(ii) This embayment infilled with superficial deposits and particularly with impermeable boulder clay, the upper limit of which rises to an exceptionally high level on the hillside.

(iii) The underlying solid rocks dip down the valley side towards Aberfan and are highly fissured. The sandstones contain water in the fissures under a hydrostatic head and are underlain by an impermeable bed (Brithdir Seam and Seatearth). The latter prevents downward percolation of the water to the deeper rocks.

(iv) (a) The boulder clay cover prevents direct flow of water from these sandstones to the surface.

  (b) The deep sections of boulder clay, infilling the old valley on the south side of the tip complex, restrict or prevent the normal 'down dip' flow of the water from the sandstones under the tip complex.

(v) Mining subsidence has resulted in:

  (a) A higher proportion of rain water entering the regional rocks through fissure systems—as groundwater.

  (b) The presence of a narrow zone of extensional strain underlying the region of Tip No. 7, and resulting in modification of the already established joint system into open fissures nearer the surface, thus providing ready access for underground water flow in the sandstones.

  (c) The presence of a major compression zone due to the effects of mining subsidence on the south side of the tipping complex provides a basin structure within which the joints would tend to be closed nearer the surface. This is a contributory factor in restricting the 'down-dip' flow of water from the Tip Complex sandstones.

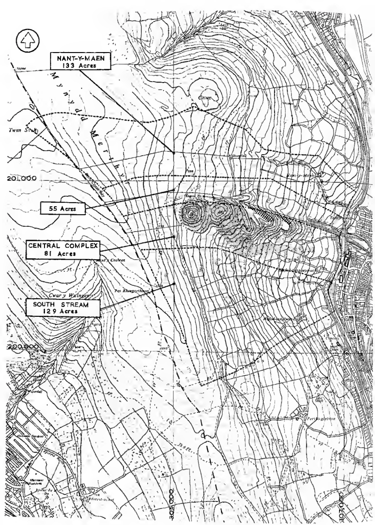
The effect of this combination of circumstances is to cause a local rise in the water level in the sandstones under the tipping area until it reaches a height where it flows over the edge of the boulder clay whence it would normally escape by surface drainage channels.

In the present circumstances this water has been introduced into the tipped material and ultimately in conjunction with the slope of the ground, and in the presence of plastic boulder clay has led to a condition resulting in the failure of the base of the tip. This was followed by the release of the main body of water.

The prime cause of the catastrophe was therefore geological.

I TOPOGRAPHIC DETAILS

The Taff Valley at Merthyr Vale and Aberfan is asymmetric in cross-section with an eastern side to the valley which is steep and upon which surface slopes range between 1 in 1·6 and 1 in 2·5. The western side of the valley which forms the substance of this report is typified by gentler slopes.



5.1 Location plan showing catchment areas

1 Topographic features

Western side of Taff Valley

Inspection of the Ordnance Survey contoured map (Fig. 5.1) indicates the presence of three topographic units as follows:

(i) *Northern Area*

This unit lies east of Cnwc, extends southwards through Nant-y-Maen and is characterised by surface contours which have a predominantly north trend. The average slopes of the valley sides range between 1 in 2·88 and 1 in 3·25 with the steeper slopes tending to occur above the 800 ft contour where by reason of control by the geological succession there is less uniformity of slope.

(ii) *Southern Area*

From the neighbourhood of Hafod-tanglwys Isaf southwards the surface contours show a predominant north-east or north-north-easterly trend. The average slope of the valley side ranges between 1 in 2·88 and 1 in 4 with the steeper gradients occurring on the higher parts of the hillside, particularly above the 900 ft contour.

(iii) *Central Area*

The region lies between the limits of (i) and (ii) above and exhibits swinging curved contours which in parts of their course follow a north and north-north-westerly direction. The area is characterised by overall gentler slopes which show a progressive range of gradients from 1 in 3 above the 900 ft contour through 1 in 4, 1 in 5, 1 in 5·6 descending the valley side to a position adjacent to the abandoned railway lines. It is on a part of this central area that the Tip Complex is situated, extending from about 1175 A.O.D. to *circa* 625 ft A.O.D. This area of gentler surface gradients lies immediately west of Merthyr Vale Colliery and from a purely topographic point of view offered an advantageous site for colliery waste disposal.

2 Topographic control

In the areas (i) and (ii) above there is a general topographic similarity, and this is directly related to the geological sequence and structure of the solid or consolidated rocks which form the valley sides. The detailed topographic features are principally decided as a result of differential erosion of the relatively hard and softer rocks in that succession. The precise position and direction of these features is dependent upon the disposition or structure of these rocks on the valley side. In the Central Area (iii) only the higher part of that region above approximately 900 ft is subject to this type of control. The lower and gentler gradients are related to a changed geological circumstance which involves the presence of unconsolidated superficial deposits concealing the solid rocks. These deposits have a structure and a distribution pattern which is markedly different from that of the consolidated strata.

There is therefore a relationship between topographic detail and geological sequence and structure along this portion of the western slopes of the Taff Valley.

II SURFACE DRAINAGE PARTICULARS

1 General introduction

The principal source of water on hillsides is derived from rainfall, other sources, e.g. snowfall, may be locally or temporarily important, and atmospheric precipitation in the form of dew though realistic in quantity is of subsidiary importance. The disposal of rainwater on a hillside is effected in the following three ways:

- (i) A proportion of the total rainfall enters the surface rocks to provide an underground storage, some part of which may later be recirculated as seepages or springs.
  - (a) Water will enter the rocks if the latter are porous, i.e. voids are present between the grains when the water fills the voids and saturates the rock to e level referred to as the water table.
  - (b) Water will also enter the rock if the latter is permeable, i.e. the water is able to traverse the rock through joints, fissures or fractures, and under certain conditions water will be stored in the joint system under a hydrostatic head.
  - (c) Ready intake of water will occur if the rock is both porous and permeable.
- (ii) A proportion of the total rainfall collects on the surface into drainage channels as 'run off' water. This proportion is higher on impervious rocks such as clays and on non-porous or impermeable rocks. The proportion also depends on the surface gradient.
- (iii) A proportion is directly returned to the atmosphere by evaporation and is climatically dependent in its proportion.

On the hillside such as the western slopes of the Taff Valley near Merthyr Vale and Aberfan these proportions are normally set and stable since they depend upon the physical characters of the rocks and their geological structure, and upon climatic factors. Under these conditions the normal processes of collection of 'run off' water into channels and streams leads to a deepening of the water courses and lengthening of the active stream section by headward erosion in time.

Any change in this normal process, e.g. retreat of the stream flow with time, indicates a change in the proportions of water disposal referred to above. Since the climatic factor is relatively constant, and the porosity of the rock is fixed by its constitution, the only effective change possible is in increased permeability. This effectively allows a greater proportion of water to enter the rocks underground and significantly less water to collect as 'run off' water.

It is shown in a leter section (IV.2.1) of this report that certain sandstones, such as the Brithdir Sandstone which forms part of the sequence, are non-porous but permeable by reason of the system of joints contained in the rock. Any process which causes these joints to open would increase the permeability and admit more water into the open joint system. The water would follow the open joints down the inclinetion or dip of the strata. The processes referred to above may be natural in the case of a strongly jointed sandstone on a hillside, particularly when the bed of sandstone either dips or has a component of dip in the same direction as the slope of the valley side. Slight tilting or slipping under the action of gravity would open up the joints. Alternatively, differential settlement of jointed sandstone blocks resulting from regional or local mining subsidence would have the same effect.

The result would be to decreese the proportion of 'run off' water leading to retreat of the stream sources to points where reasonably permanent supplies from seepages, springs or issues emanated from stored water. Such features are demonstrated for the surface drainage of the Merthyr Vale–Aberfan area.

2 Details of the Merthyr Vale–Aberfan drainage

1 *Evidence for retreat of drainage system*

Figs. 5.2, 5.3, 5.4 and 5.5 indicate the positions and extent of stream courses within and adjacent to the tip complex for the period between 1868–75 and 1966. The figures have been compiled from the following nine Ordnance Survey maps:

	Scale	Edition of	Date of Survey	Date of Survey revision
1	1/10560	—	1868-73-4-5	—
2	1/2500	1900	1873	1898
3	1/2500	—	1875	—
4	1/2500	1912	1873	1898
5	1/2500	1919	1873	1914
6	1/10560	1921	1868–73	1914
7	1/10560	—	1868–73	1914 with additions in 1948
8	1/2500	National Metric Grid	1956–57	—
9	1/1250		25th October 1966	—

Notes:

(1) The interpretation of the symbolisation for streams and water courses shown on the foregoing list of maps is a matter of opinion.

(2) 1/10560 signifies a scale of 6 in. to a statute mile.

(3) 1/2500 signifies a scale of 25·344 in. to a statute mile.

Fig. 5.2 shows the position and extent of streams from 1868–75 survey.

Fig. 5.3 shows the position and extent of streams from 1898 survey.

Fig. 5.4 shows the position and extent of streams from 1956–57 survey.

Fig. 5.5 shows the position and extent of streams from 25th October 1966 survey.

1868–75 survey (Fig. 5.2), 1898 survey (Fig. 5.3)

These surveys are closely comparable, the major streams are well established throughout their length and the 1898 survey shows extension of one tributary of the South Stream and of a small stream within the Central Complex. On the other hand the southern tributary of the larger stream within the Central Complex is not represented on the 1898 survey.

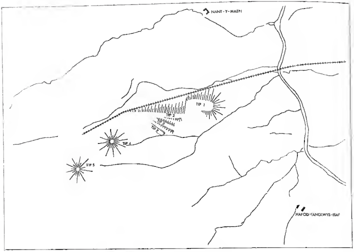
1956–57 survey (Fig. 5.4)

Comparison of the stream courses at this survey with those of earlier surveys indicates very considerable retreat of all streams. The sole exception is the middle tributary of the South Stream. This general retreat is considered to indicate decreased 'run off' water and corresponding increase in ground water by changed permeability of the sandstones forming the hillside. The survey of 1956–57 was carried out at a time when it is considered from the evidence of others that subsidence due to deep working was completed, i.e. before 1957.

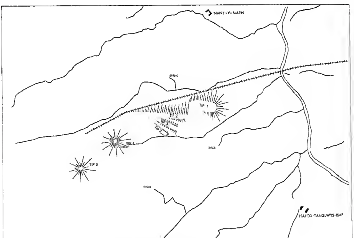
1966 survey (Fig. 5.5)

In general this survey is comparable with that of 1956–57 although modifications have taken place within the Central Complex to which later reference is made. Several streams show extension of their courses, notably the northern tributary of the South Stream and the stream immediately north of the tip complex.

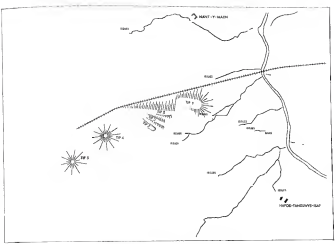
The inference is that there have been significant changes in the drainage of this region and particularly between the surveys of 1898



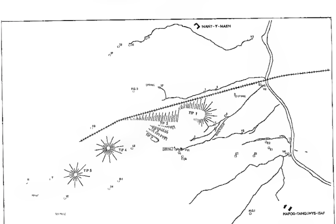
5.2 Position and extent of streams from 1868–75 survey.



5.3 Position and extent of streams from 1898 survey.



5.4 Position and extent of streams from 1956–57 survey



5.5 Position and extent of streams from 1966 survey and 1956–57. These changes have resulted in a greater proportion of the rainfall entering the rocks as ground water and this was brought about by increased permeability along joints and fissures and is mainly the result of regional mining subsidence effects.

2 *The streams: catchment particulars and water flow*

Figs. 5.2, 5.3, 5.4 and 5.5 show the position of streams and water sources within the tip complex and adjacent to this complex prior to and subsequent to tha tipping of colliery waste. For each of the main drainage channels the catchment area has been calculated in acres as shown on Fig. 5.1.

Four main streams drain this area, and it is appropriate to consider in some detail three of these streams in order to relate certain factors. These are:

(a) Relationship between volume of water carried by stream and the area of catchment.
(b) Relationship between type of water carried in the stream and rock types over which it flows in the catchment area.
(c) The establishment of the main source of water in the tipped area from consideration of relationships (a) and (b) above.

For this purpose, metering of three streams has been carried out and analyses of the water in the streams and at other points within their respective catchment areas have been completad. These facts are referred to at appropriate points in this report. The three streams chosen for comparative purposes therefore have differing catchment areas, two have similar geological conditions over their catchment area and the third drains the tip complex. They are:

(i) Nant-y-Maen, a stream draining the hillside north of the tipped area.
(ii) The unnamed stream now designated the 'South Stream' which drains the hillside south of the tipped area.
(iii) The main drainage from the tipped area designated the 'Central Complex'.

A *The streams and catchment particulars*

(i) *Nant-y-Maen.* Catchment area above disused railway, 133 acres.

This stream drains a long and relatively narrow strip of the valley side well north of the tip complex, and is fed from surface 'run off' water and by seepages from the beds of sandstone which outcrop along the valley side. Only in the lower reaches of the stream is boulder clay present, and thus this stream is representative, in quantity and quality of its water, of a stream which drains and flows over the rocks exposed on the valley side.

(ii) *The 'South Stream'.* Catchment area 129 acres.

This stream, south of the tip complex, is formed by the confluence of three tributaries which drain a roughly triangular area of the valley side. It is fed from surface 'run off' water, and from seepages and small springs which issue from the various beds of sandstona outcropping along the valley sides. A small area of boulder clay is present within the lower reaches of the catchment area. This stream both in size and nature of its catchment area is similar to that of Nant-y-Maen, and like that stream is representative, in quantity and quality of its water, of a stream which drains and flows over the solid rocks exposed on the valley side.

(iii) *The 'Central Complex'.* Catchment araa 81 acres.

The courses of the original stream which drained this elongated strip of catchment are shown in Fig. 5.2, from which it is seen that tipping extended over the headwaters of a stream.

On the upper part of the catchment area solid rocks form the valley side and there the stream would be fed by surface 'run off' water and from seepages from the beds of sandstones. An impervious layer of boulder clay covers the solid rocks over the lower part of the catchment area and stream flow in this region would be fed from an intensified surface 'run off' water on top of the clay. It is possible that seepages of groundwater from the underlying sandstones were present at various points along the edges of the boulder clay. In the lower reaches of the catchment area a sandy deposit overlies the boulder clay and seepages through the sand would also contribute to the stream flow. The nature of the original catchment area thus differs from that of the streams referred to in (i) and (ii) above.

The position of the main stream draining this area subsequent to earlier tipping is shown on the 1956–57 Ordnance Survey Plan (see Fig. 5.4). On this plan the commencement of the stream is shown as three points of 'Issues' all of which appear to lie on or near the edge of the then tipped material, and all of which occur on the boulder clay covered area.

On 21st October 1966, water in great quantity broke out from the 'New Spring' (shown inscribed as Spring in Fig. 5.5). This 'New Spring' which has, subsequent to 21st October 1966, continued to flow, lies 50 yards west of one of the 'Issues' marked on the 1956–57 Ordnance Survey plan and 33 yards north-east of a second 'Issues' shown on that plan. There is no evidence to suggest that the 'New Spring' is the same as those previously marked 'Issues'. This is particularly the case in view of the fact that a substantial make of water continues to appear from out of the tip material at points along the southern margin of Tips Nos. 1, 2 and 4, i.e. along the line of the old stream. (These points are referred to later as water sampling points 5, 6, 7 and 8.)

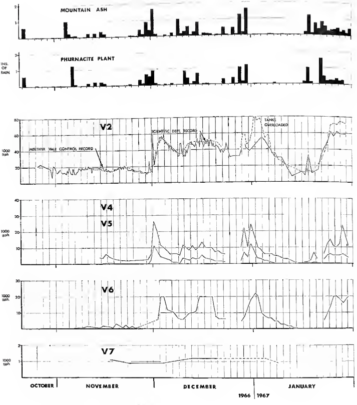
Table 1
Estimates and measurements made during the three days following the morning of the disaster

Date	Time	Site	Flow gph	Remarks
Friday, 21st October, 1966	13.00	Main issue from tip at source	400,000	Estimated in retrospect against flow measured on Sunday, 23rd October 1966. Estimate by D. Bowen. Water issuing as mudflow from approximately 10–16 ft up face on a width of approximately 30 ft. Not clear whether any discharge lower down face than this.
Saturday, 22nd October 1966	16.50	Main stream approximately 100 yards from source	234,000	Measurement based on width, depth and velocity. Water issuing as clear stream from bottom of a 7 ft wall of clay. Measured by P.M. Grant.
Sunday, 23rd October 1966	08.00	Main stream at outfall to canal	210,000	Estimated by observation of pumps and water in canal. Estimate by G.A. Jones.
	15.50	Main stream about 100 yards from source	100,000	Measured on basis of channel width, depth and velocity. Measured by D. Bowen.
	16.00	Ditto	130,000	Measured on basis of channel width, depth and velocity. Measured by P.M. Grant.

B *Water flow*

Appendix Ia to this report (see Fig. 5.6 and Table 1) contains measurements and some estimates of the water flow from the tip complex, from Friday, 21st October 1966, to 31st January 1967. Measurements of water flowing from the three sources and measured by V-notches have been made at water sample and measuring points shown on Fig. 5.5 as follows:

(i) Nant-y-Maen: since 14th–15th November 1966.



5.6 Measurements of water flow and rainfall.

(ii) 'South Stream': since 14th–15th November 1966.
(iii) 'Central Complex': since 31st October 1966.

The results of these investigations are expressed graphically in Fig. 5.6 and the flow in thousands of gallons per hour is related to date and to rainfall figures. On this graph:

V3 represents virtually all the drainage water from the Central Complex;
V6 represents a part of this flow emanating from the 'New Spring' and separately measured;
V4 represents the flow from the 'South Stream';
V5 represents the flow from Nant-y-Maen.

The following facts are illustrated by this graph:

1. Despite similarity in catchment area and geological particulars of the streams (i) Nant-y-Maen and (ii) South Stream, there is great disparity of water flow between these streams. That of Nant-y-Maen is very reduced in quantity, suggesting greater underground water feed from this catchment area which is 'up dip' of the tip complex.
2. The 'New Spring' itself has a flow which totally exceeds the flow from Nant-y-Maen, and for certain dates also exceeds that of the South Stream.
3. V4 and V5 show agreement in pattern of flow as surface streams; this pattern is in the form of an exponential curve. The 'New Spring', V6, does not follow this pattern, but continues with a fluctuating rise and fall when the surface drainage has decreased. There is a delay period of two or three days between the rainfall record and the flow volume of the spring, indicating an underground source for V6. Similar features are seen in a comparison of V3, with the surface stream flow of V4 and V5.
4. The total flow from the Central Complex as shown by V3 is vastly greater than that from Nant-y-Maen or the South Stream or indeed of the flow from both streams combined. This amount of water is greatly in excess of what would be expected, bearing in mind that the catchment area of 81 acres is considerably smaller than the catchment of Nant-y-Maen (133 acres) or the South Stream (129 acres). This is in part accounted for by a greater proportion of surface 'run off' water on the superficial clays which form part of the catchment area of the Central Complex.
5. There appears to be a general relationship between the graph V3 and rainfall where information is complete. Thus three days of heavy rainfall, 4th–7th November 1966, corresponding with fluctuating low and high records on these dates from V3. The general rise in V3 occurred between 9th and 12th November 1966, i.e. approximately a two or three-day delay period between rainfall and V3 records. Similarly the last period of rain on 17th November is immediately followed by low V3 records until 20th to 22nd November 1966 when the flow of V3 increased again. Further examples of response to rainfall can be seen for the periods 29th November to 2nd December, and from 28th to 30th December 1966.

The following inferences may be drawn:

(a) The Central Complex yields an amount of water greatly in excess of that from adjacent catchment areas and with a flow pattern which is not the same as that for surface 'run off' drainage from stream sources.
(b) Water is collecting under this area as groundwater in the rocks; this is known to be discharged at *at least* one point, viz. 'New Spring'.
(c) The feed into the groundwater from rainfall is rapid, a delay period of two days has been proved since records have been kept. This entails rapid collection and movement of groundwater through open joints.

3 *Chemical analyses of waters*

Appendix Ib to this Report contains a statement on the sampling and analysis of waters from the Merthyr Vale Colliery and surrounding areas. The sampling points are referred to the National Grid Reference, and shown on Fig. 5.5 as water sampling and measuring points.

The water from Nant-y-Maen and from the South Stream has been sampled. These samples are included in a group of analyses concerning which the analyst concluded in his report: 'All of these waters are characterised by their high quality, having very low mineral content with consequent very low permanent and temporary hardness.'

With regard to water from the main sources within the Central Complex, this is covered by the sampling points Nos. 3–7 at springs. In general the analyst reported: 'Analyses of these waters show that they are broadly of similar type and are probably natural groundwaters. The high rate of flow from sampling point 4 ("New Spring") and the marginally higher but constant temperature suggests an underground spring.' The water from sampling point 8 represents surface drainage from Tip No. 1, but its analysis is generally similar to the other analyses from sampling points 1–7, and is generally similar in type to water from sampling points 3–7 which are on a main drainage course. With regard to sample 8 the analyst referred to absence of mineral acidity and a very low concentration of aluminium, potassium, iron and silica, and considers this to indicate lack of chemical breakdown in the shales of the tip. Later analyses from sample point 4 ('New Spring') showed 'Very considerable increases in calcium, magnesium, sodium, and sulphate contents'. Similar changes have occurred in the composition of the waters from sampling points 3, 5, 6, and 7, but these have only been marked in the case of sample point 6.

This might possibly result from a fall of the underground water level in the case of sample 4, as a result of spring flow decreasing this level. Some adjustment of drainage would follow which may introduce contamination into the water from local sources.

It appears possible that the springs issuing from the Central Complex area, and within and adjacent to Tip No. 7, have a common origin. Their compositions are influenced by the leaching action of rain on the tip, with some seepage into the ground beneath.

III THE GEOLOGICAL SUCCESSION

The geological succession present on the western slopes of the Taff Valley above Merthyr Vale and Aberfan forms part of the Coal Measures succession which is well known in most of the valleys of South Wales. In particular it consists of the upper part of these measures to which the general term of Pennant Measures or Pennant Sandstone is commonly applied. This succession of rocks forms by far the greater part of the valley side and constitutes the solid rocks which outcrop to give featuring on the valley side. Over some part of the valley side, normally the lower reaches, these solid rocks are concealed by a variable thickness of superficial deposits of a much later age, and it is therefore pertinent to describe the geological details of succession under two headings:

1. The Solid Geology
2. The Superficial Geology.

The geological succession has in the past been the subject of considerable study by several workers, including the writer of the present Report, and is covered by the Geological Survey Map, Glamorgan 19 N.W. (1 : 10560). The region was re-surveyed in 1945 and a Geological Map published in 1964, the relevant details are included in the Geological Survey Memoir, *The Geology of the South Wales Coalfield, Part IV: Pontypridd and Maesteg*, 1964.

The accompanying Geological Succession Chart (Fig. 4.1) serves to illustrate the Geological Map (Fig. 4.2). Both are largely based on the published Geological Survey Map and Memoir, with such detailed additions or modifications which recent borehole or geophysical investigation has made possible.

1 The solid geology

The solid rocks outcropping on and underlying the valley side are depicted in the vertical section (Fig. 4.1). They commence at a coal seam known as the No. 1 Rhondda Rider Seam which outcrops at the surface near the valley bottom. The succession continues up to the sandstone which overlies the Cefn Glas Seam with an overall thickness of some 700 ft of strata. The sandstone overlying the Cefn Glas Seam forms the summit of Mynydd Merthyr. The sequence includes a part of the Rhondda Beds, the whole of the succession of the Brithdir Beds, and the lower part of the Hughes Beds as defined in the recent 1964 Geological Survey Memoir.

From the No. 1 Rhondda Seam at the base, up to the Brithdir Seam there are some 280 ft of rocks. This succession is poorly exposed but has been proved in borehole H.G.2. The rocks include beds of sandstone, siltstone, mudstones and some thin coals, one of which was previously exposed behind Nant-y-Maen Farm. Some 27 ft below the Brithdir and separated from it by a belt of mudstones is another coal seam. This coal has been proved to be present both north and south of the tipping area, but whether it represents a separate seam or the lower part of the seam proved in borehole R.5 and H.G.1 is not known. Immediately below the top coal, the Brithdir Seam, is a clayey seatearth.

The Brithdir Seam was formerly worked from an old level near Haford-Tanglwys-Isaf, where the seam had a thin section as follows:

Clift end rock	
Coal	1 ft 4 in.
Fireclay and ironstone	4 ft 6 in.

Borehole R.2, which was cored, recently proved old workings in this seam and the underlying seatearth. In borehole R.7, which was drilled a short distance away, the driller recorded a void at the horizon of the lower seam. There is thus some evidence for old workings in the lower seam also. The coal seam (R.2) was immediately overlain by 2–3 ft of carboneceous mudstone with contained coal bands, upon which rested in turn a thick, massively jointed current bedded sandstone. Some 75 ft of this sandstone was proved by the borehole. This same sandstone is present in a quarry at Aberfan where 30 ft of messive, strongly jointed current bedded sandstone is exposed. From surface mapping and as a result of recent borehole evidence it appears that the bulk of the sequence between the Brithdir Seam and the Cefn Glas Seam (about 360 ft) consists of sandstone at Aberfan. In some localities a thin coal or seatearth horizon is known to be present within this sequence and is then known as the Brithdir Rider Coal. Exposures of sandstones at about this horizon are visible at the surface on the summit of Cnwc 700 yards north of the tips, where they form crags of massive and jointed current bedded sandstone. The Cefn Glas Seam overlies the sandstones of the Brithdir Beds and is itself both underlain and overlain by mudstones or shales, intercalated into a predominantly sandstone sequence and forming thereby a line of seepage along the feature produced. The sequence is continued by a further thick bed of sandstone which reaches up to the summit of Mynydd Merthyr and is exposed there.

The vertical section (Fig. 4.1) shows that the Brithdir Seam marks a very pronounced change in the lithological characters of the rocks in the succession. Above the Brithdir Seam the succession consists almost entirely of thick beds of sandstone. These massive grey sandstones contain sub-angular to sub-rounded grains of sand or other rock fragments bonded together by a fine matrix of silica and clay minerals. Their porosity is low but permeability may be high when the rocks are jointed and the sandstones are therefore water-bearing. Below the Brithdir Seam its fireclay forms an impervious layer and the mudstones and siltstones are relatively impervious unless badly jointed. This position in the sequence is of importance since permeable beds above and impervious beds below are in conjunction and downward percolation of the groundwater ceases at this level. Seepages or springs thus normally issue from a spring line at about this horizon. In this respect it is to be noted that many landslips in the eastern valleys of South Wales are known to originate at this position in the sequence. These have been described by Professor G. Knox (1928), 'Landslides in South Wales Valleys' (*Proc. S. Wales Inst. Engrs.*, Vol. XLIII, pp. 161–233).

The shales associated with the Cefn Glas Seam horizon overlie the sandstones of the Brithdir Beds. Borehole R.10 proved that two thin coals are present at the Cefn Glas Coal position and are underlain by 120 ft of shales containing other thin coals. For similar reasons to those referred to above the Cefn Glas Coals, fireclay and shales also mark a point of issue of seepages and springs, and the position on the Geological Survey 6-in. maps is indicated as a spring line.

2 The superficial geology

The Geological Survey Map shows a deposit of boulder clay which runs along the lower slopes on the western side of the Taff Valley and which extends in a tongue up the side of the valley in the vicinity of the tipping area, reaching as high as the 900 ft contour. The boulder clay is ground moraine left by the lobe of a glacier which at one time filled and moved down the Taff Valley; it has been observed in sections exposed in the streams, and in borehole cores and pits which have been sited to explore its extent and thickness. The Geological Survey Map also shows the boulder clay to be overlain in part, and particularly on the lower slopes, by glacial 'sand and gravel', a variable deposit both in constitution and thickness formed as outwash material during the retreat of the melting glacier.

A further unconsolidated deposit is present and has been observed in the stream and trenches as a yellow, often ochreous, sandy clay containing angular fragments of rock. On the upper valley slopes this material overlies the solid rocks in part, and lower down it overlaps and covers the boulder clay in places. This material ,known as 'Head', was formed from the downwashing of weathered rock debris along the valley sides, and also in part from redistribution of the weathered boulder clay and soil. These various unconsolidated superficial deposits are present on the hillside west of Aberfan.

The extent of the boulder clay has been confirmed by recent drilling and by geophysical survey, and details are included in a separate section of this report (IV.3).

The unconsolidated superficial materials were deposited against the exposed and already weathered edges of the solid rocks along the valley side as a blanket concealing their outcrop, at a time during or immediately following the Ice Age. They are therefore geologically speaking very 'recent' in age. By their mode of formation and by the nature of the material deposited the deposits tend to be variable in thickness and composition, and were left on the hillside filling pre-existing hollows which were once a feature of the pre-glacial landscape. These deposits therefore obscure the pre-glacial form of the hillside, and the tongue of superficial material which extends up the hillside to 900 ft west of Aberfan marks the site of an original pre-glacial hollow cut by water or by the action of ice. Since the Merthyr Vale Colliery shafts proved the presence of rock head at 60 ft below the present level of the River Taff at that point, it is conceivable that a very considerable embayment is represented beneath the tongue of boulder clay which rises up the valley side to 900 ft west of Aberfan.

The boulder clay consists of a dark grey-brown yellow weathering tough stony clay which is often soft and plastic when wet.

Near its base the boulder clay is seen to contain large angular blocks of sandstone which are cemented together by clay. Such a deposit resembles surface scree or talus material covered by the boulder clay. During its formation and deposition the clay was forced by the movement and weight of ice into fissures and fractures on the then weathered and exposed surface of the solid rocks. The clay is impervious and certain details concerning this property to prevent transference of water are given in Table 2.

The glacial sands were exposed in a recent trench and there seen to consist of yellow, grey or vari-coloured clayey sand which both contains water and allows the movement of water, thus accounting for a number of small springs on the southern part of the Central Complex. Their presence is essentially due to the variable or heterogeneous nature of this deposit.

Table 2
Laboratory Permeability Tests

Cores	Permeability	
	ft/day	gal/sq. ft/day
Brithdir sandstone (Sample 1)	3×10^{-5}	2×10^{-4}
Brithdir sandstone (Sample 2)	5×10^{-5}	3×10^{-4}
Boulder clay (Sample 3)	Poor specimen	
Boulder clay (Sample 4)	5×10^{-3}	3×10^{-2}

The core permeabilities were determined by the variable head method in the Divisional Scientific Department of the National Coal Board, South Western Division.

3 Age and structural relationships of the solid rocks and superficial deposits

The Coal Measure rocks of the Taff Valley were formed, consolidated, lithified, compressed and finally folded, faulted and a fracture or joint system instituted in a cycle of events which was essentially completed soon after the end of Carboniferous time, *circa* 200 million years ago. During subsequent geological history, the rocks and their structures have been uplifted and eroded, and possibly buried by other rocks which have since been worn away. Finally, within the last *circa* 1 million years, a condition resembling the present landscape and its main drainage was instituted and the old structures of the solid rocks formed this surface. These structures and the sequence of rocks involved exerted a control on this early landscape. Subsequently a tongue of ice or a glacier moved down the Taff Valley and modified the valley form by planation of solid rock in places and by the deposition of their ground-up remains in the form of boulder clay in the pre-existing hollows at other places.

Such a hollow is that west of Aberfan, where it is presumed by reason of structural weakness in the solid rocks, either of incipient flexuring, or of heavy jointing associated with the Kilkenny Fault, there had been pre-glacial erosion possibly by water action from springs or streams. Certainly it was a hollow into which ice from the main stream moved as a lateral lobe. The hollow may have formed an incipient cirque or cwm as a small supply centre of ice from time to time. Under either of these conditions ice shattering would increase the disruption of sandstone blocks and open up the already established joint and fissure system, and so provide angular talus material. Boulder clay would follow the form of the main ice in the valley and be forced into these fissures, and be deposited as a blanket coinciding with the form of the valley side and bearing no structural relationship with the solid rocks below beyond that of filling hollows previously existing within them.

The glacial sands formed from outwash streams from the retreating ice are less regularly distributed, and more dependent on the positions at which streams issued from the ice.

The inference to be drawn is that the area in question west of Aberfan represents a particular geological condition in the Taff Valley. This condition is ascribed to some early structural features with attendant hydrological characteristics. The presence of boulder clay indicates this fact but conceals the actual features and the extent of the boulder clay indicates the area of the particular conditions.

It is a matter of some interest that the Geological Survey Map also indicates a triangular tongue of boulder clay ascending the opposite and eastern side of the Taff Valley near Merthyr Vale. The northern limit of this boulder clay with the solid rock is the line of the Llanfabon Fault and this area of boulder clay is therefore structurally controlled on its northern side. The fault runs across the lower ground of the floor of the valley and does not appear to affect the area of boulder clay at Aberfan. This same Geological Map shows a change of direction in the conjectural outcrop of the Brithdir Seam on the west side of the valley. The change of direction takes place in the vicinity of the boulder clay cover at Aberfan, and may indicate some degree of flexuring in the solid rocks.

IV THE GEOLOGICAL STRUCTURE

1 General geological structure of the western side of the Taff Valley

The solid rocks from the horizon of the No. 1 Rhondda Rider to the sandstones above the Cefn Glas Seam form the valley side and underlie Mynydd Merthyr. The regional dip as proved by field mapping and in underground seam workings varies from 1 in 10 to 1 in 14 (5°–4°) in a general direction South 31°–34° East (149°–146°). Slight variations in the dip occur on the higher valley slopes. This simple structure ensures that each successive bed in the sequence of solid rocks occurs high on the hillside at the northern end of the Taff Valley and then at progressively lower levels on the valley side southwards until the floor of the valley is reached. The solid rocks generally form most of the hillside and exposures of the sandstones are seen in various natural crags and in small quarries. A mantle of detritus, formed from weathered rock and of varying thickness, may cover the solid rocks on the higher slopes.

The Kilkenny Fault forms a very important geological boundary to the west, its surface position can be mapped with reasonable accuracy near the crest of Mynydd Merthyr. The fault trends South 33°–40° East (147°–140°) and therefore follows a direction which is very close to that of the dip of the beds of solid rock. The fault downthrows in a north-easterly direction, i.e. towards the valley side, by an amount of some 288 ft in the lower seam workings. From the intersection of the fault in the various seam workings the average inclination of the fault plane is calculated at 54°–55°. Utilising this inclination, the fault plane will pass under the western edge of Tip No. 5, at 1639 ft B.O.D., and beneath the position of the 'New Spring' at 2600 ft B.O.D.

The solid rocks are characterised by the presence of strong joints and fissures which show a regular pattern of direction and which are related to the action of the Kilkenny Fault. The particulars of the joint pattern are given in section IV.3.2; they form an essential part of the considerations of geological structure.

On the middle and lower valley slopes the solid rocks are covered by a variable thickness of boulder clay and in places by additional overburden of glacial sands. This is particularly the case in the area west of Aberfan in the vicinity of the tip complex.

2 Particular geological structure in the vicinity of the tip complex

The Aberfan Geological Plan (Fig. 4.2) indicates the respective outcrops of (1) solid rocks, and (2) superficial deposits over this area.

Figs. 4.3 and 4.4 incorporate the surface geology of Fig. 4.2 and additionally contain relevant information from deep mining. They represent true scale geological sections across the area from west to east and from south to north respectively, and thereby record the geological structure.

1 *Solid rocks*

(i) *Rhondda Beds.* That part of the sequence included in the Rhondda Beds and indicated by grey colouring, only outcrop on the lower western slopes of the region in the northarn sector of the map, at other points they are concealed by superficial deposits.

(ii) *Brithdir Beds.* The position of the Brithdir Seam and fireclay which forms the base of this succession is established by old and shallow workings west of Aberfan Cemetery and by an exploratory borehole R.2 to the north. The coal seam is not exposed in the southern part of the area, since it is also concealed by boulder clay. The line of its presumed outcrop beneath the boulder clay is raasonably established by exploration, and its outcrop would pass beneath the toe of Tip No. 2, as indicated. The thick mass of Brithdir Sandstona (some 350 ft thick) which overlies the Brithdir Seam up to the Cefn Glas Seam forms the broad area of outcrop coloured in green wash. These sandstones are in general exposed except for the area of sandstone concealed by boulder clay and where in places other superficial detrital material is present. Thase sandstones also underlie the whole area of the hillside between the Cefn Glas Seam outcrop and the Kilkenny Fault.

(iii) *Hughes Beds.* The Cefn Glas Seam, its seatearth and attendant mudstones and shales form a flat-lying feature resting on the Brithdir Sandstones and from this junction springs and seepages are recorded. The higher part of the hillside over the crast of Mynydd Merthyr is occupied by the thick sandstones which overlie the Cefn Glas Seam shown in ochre wash and indicated H.S. on the map. Thase sandstones are abruptly cut off by the Kilkenny Fault. By reason of the throw of this fault the Brithdir Sandstones again form the surface on the western side of the fault. There is therefore a very considerable area of this map over which the Brithdir Sandstones outcrop at the surface, and a further region on tha downthrow side of the Kilkenny Fault where they underlie the Cefn Glas Seam and its sandstones. These facts are demonstrated in the Geological Section A-B (Fig. 4.3).

The regional dip of the solid rocks is 1 in 10 and 1 in 14 (5°–4°) in the general direction South 31°–34° East (149°–146°), but variations in the direction and value of dip occur in the rocks forming the higher valley slopes. These are due to variations in the regional strike of tha beds which occurs adjacent to the Kilkenny Fault. In the Seven Feet Seam workings the seam contours swing from a trend of North 50° East (50°) to North 15° East (15°) adjacent to and in the downthrow side of the fault. The dip also increases from 1 in 13 to 1 in 11 to produce flexures. In the lower seams this change in trend of the contours commences some 300 yards east of the fault.

The position of the Kilkenny Fault is known at the surface and underground at Merthyr Vale. One mile south of Marthyr Vale on the western side of the Taff Valley under Cefn-y-fan the Kilkenny Fault Plane is exposed and controlled to some extent the position of a landslip which affected the Cefn Glas Sandstones on its downthrown side. The tumbled masses of sandstone involved show the jointed and fissured condition of the Cefn Glas Sandstones near the fault line.

The Kilkenny Fault, with a trend South 33°–40° East (147°–140°), is a major fault approximately following the line of true dip, and is one of a number of other faults shown on the map with similar directions. The Kilkenny Fault as a normal type fault expressed a state of tension in the rocks of its downthrown north-easterly sida. Three small accommodation faults all downthrowing west and trending roughly parallel to the Kilkenny Fault were proved in the Brithdir Seam workings, and are shown affecting the Brithdir Sandstones on the present Geological Map. The throws of these faults are comparatively small at 4 ft on one fault, and with a range of 4–15 ft on the second, and to 9–30 ft on the third. The position of these faults indicates the general extent of the workings on the Brithdir Seam; one of these faults extends to near borehole R.4. Two further faults of similar trend have been proved by borehole exploration. One following the line of a prominent surface fissure intersects the Cefn Glas Seam and is shown on the Geological Map. It was proved by boreholes R.9 and R.10. The other fault lies between boreholes H.G.2 and H.G.3. Measurement of joint and fissure directions in the higher sandstones show the presence of two main sets of joints:

Set A at 34°–38°
Set C at 123°–131°.

Set C is reasonably near the trend of the Kilkenny Fault (147°–140°) and likely to be associated with its tensional movement. This set of joints is also near the direction of the dip, and varies from this direction through a range of 15–26°. Such dip joints, inaugurated by fault movement, would allow collection and transference of water down the dip of the beds.

Set A is at 65°–72° to the dip direction and approximately at right angles to Set C, they are thus very nearly strike joints and would provide water collection, storage and flow in this direction.

Set C joints are approximately 6 ft apart, Set A at 10–12 ft intervals.

Thus the earth movements which culminated in the fracturing of the strata forming the Kilkenny Fault, also gave rise to the formation of an extensive joint system in the sandstones. The changes of dip, the flexuring, the faulting and fracturing referred to above was completed long before the Ice Age and collectively could account for a zone of structural weakness, the position of spring lines feeding a tributary valley, or later the collecting point of ice, in the vicinity of Aberfan.

2 *Superficial deposits*

The boulder clay shown in blue wash on Fig. 4.2 conceals beds of the Rhondda group, but extends up the valley side to conceal the Brithdir Seam and some part of the Brithdir Sandstones notably in the area of the tip complex. The limits of the boulder clay shown are approximately those shown on the Geological Survey Map, but modifications have been made in view of recent borehole evidence.

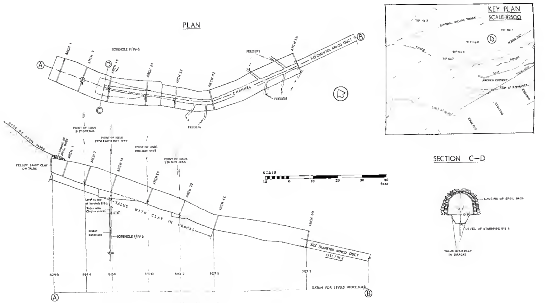
A geophysical survey was made which confirmed in general the limits of the boulder clay shown on the Geological Plan and established the depths to rock head beneath the boulder clay at various points (see Section IV.4). The present indications are that the thick deposits of boulder clay are filling a pre-glacial hollow which may have been a tributary valley. The distribution of boulder clay extending far up the valley side to a point at least 900 ft A.O.D., also suggests that this hollow was a collecting ground for ice. The deposit, in the form of a tongue tapering up the valley side and broadening at its base lower down the valley side, suggests a normal valley shape. The glacial sands (shown in pink) rest on the boulder clay and are in turn overlain by the alluvium of the valley floor.

3 Detailed geological structure underlying Tip No. 7

1 *Superficial cover of boulder clay*

Fig. 4.2 depicts the area of boulder clay as indicated in general on the Geological Survey Map, with minor modifications of line as deduced from exploration by boreholes and pits in part of its extent. The actual and precise distribution of the boulder clay over the tip complex is a matter of importance and is the subject of a separate Geophysical Survey. A geological interpretation of these results is included in Section IV.4.2.

The base of the superficial deposits was examined in the Arched Culvert (see Fig. 5.7) where the spring at Arch 14 was excavated. At this point the basal deposit consists of closely packed angular blocks of sandstone believed to represent a talus accumulation of material.



5.7 Plan and sections of the arched culvert

From the evidence of the P/IV-6 borehole this deposit appears to merge downwards into the weathered surface of the rock. Similar material with smaller angular blocks forms the floor of the Arched Culvert at lower levels, e.g. Arches 32 and 42. At all points referred to the interstices between the angular blocks are closely packed with a sandy clay, which in places is a tenaceous and plastic material. Overlying the talus deposit and originally exposed at the head of the Arched Culvert is a section some 4 ft thick. This contains, as far as inspection was possible, yellow ochreous clay with a sand content and angular fragments of sandstone. This much weaker soft clay appears to represent a deposit near the uphill limit of boulder clay at this point.

Outside the Arched Culvert and in the face of the basal slip feature there are other sections of a soft clay-like material which contains rootlets and was the soil opon which tipping took place. This material may have originally represented the collection of Head or Downwash material and is overlying the boulder clay. Such a section was exposed in the pit excavated in the cleared area immediately south of the spring where a thin layer of ochreous sandy stony clay overlay boulder clay.

Undoubted boulder clay is exposed 150 yards south of the 'New Spring' position in a diversion trench, where layers of blue-grey and brown tough clay contain occasional angular or water-worn pebbles of sandstone and show a dip of a few degrees in a northerly direction. The section is variable in thickness between 1 and 4 ft and overlain by a sandy clay with decayed organic matter representing an old soil condition. Such boulder clay has been recovered from borehole R.2 and therefore extended further uphill than the point recorded above. It is an impervious clay, and tests on this characteristic have been carried out on specimens from R.2 and are included in Table 2. A cover of this boulder clay would seal the water in the underlying solid rock, and any escape of this water would only take place where the impervious clay cover was thin, or where the clay seal was broken or subsequently eroded away.

2 *Mineralogical composition of boulder clay*

Samples of the boulder clay collected from the sides of the diversion trench were selected as representative of the softer and more plastic boulder clay. The mineralogical composition of this clay has been determined by X-ray analysis.

Finely divided quartz makes up approximately 50% of the aggregate and is associated with small quantities of feldspar and about 1% of coal fragments, the remainder consisting of clay minerals. The finer 2 micron fraction contains less quartz and consists predominantly of mica and clay minerals. The latter are predominantly kaolinite and illite with some chlorite. The properties of kaolinite and illite are such that extra-lattice layer water is *adsorbed* and in this respect illite is more reactive than kaolinite. Neither mineral *absorbs* water as an interlayer constituent since the lattices are non-expandable. The additional *adsorbed* water increases the moisture content and the plasticity with a decrease in the strength of the clay.

3 *Possible chemical effects on clay from tip water*

Analysis of the waters considered in an earlier section of this Report (Section II.2.3) indicate that some water from tip drainage contains the ions of calcium, magnesium, sodium and potassium, and that sulphate ions, principally as sodium sulphate, are present in the water. It is unlikely that these ions would have much effect on the stable minerals present in the clay, and particularly so in view of the low concentration of ions present. Thus from the empirical replacing power of ions, sodium is the only ion likely to be concerned in exchange and would not normally replace potassium in the illite lattice; when this happens there is a decrease in stability as measured, e.g. by the Atterberg Liquid Limit L.W. The sulphate ion has no effect on this property for illite, but there is an increase of stability for kaolinite.

Under a moderate concentration of sodium ions clay of this type is often flocculated.

The chemical effects of tip water are likely to be negligible and any action superficial since water in quantity would not pass through the impermeable clay.

4 *The underlying solid rocks*

Reference to Fig. 4.2 indicates the Brithdir Sandstone to be the solid rock which underlies the toe of Tip No. 7. At the location of the 'New Spring' and in the position of Borehole P/IV-6, both points within the original tip confine, the Brithdir Seam lies at a depth of 75 ft 8 in., this being the thickness of the sandstone below these levels to the coal seam. The Brithdir Seam has been proved on the south side of the tip by Borehole R.2, which reached old workings in the seam at a depth of 122 ft. Likewise Borehole R.3 (which was not cored) proved the seam at 138 ft 6 in. Borehole H.G.2 on the north side of the tip complex proved the Brithdir Seam at 76 ft. From these and three other boreholes the position of the outcrop of the seam in the solid, and below the cover of boulder clay, is as shown on the Geological Map (Fig. 4.2). Below the Brithdir Seam are its fireclay and the silty mudstones which are impermeable and prevent downward percolation of water. The seam was originally worked from levels at Hafod-tanglwys and Perthigleision, and workings extended up to the southern edge of the tip complex. These workings are shown on Plan No. H.12 and the nearest workings to the tip complex were completed in January 1869.

Some 75 ft of the Brithdir Sandstone lying above the Brithdir Seam was cored in the R.2 borehole, and the cores illustrated nearly vertical open joints, with the sandstone at the base of the joints frequently rotten. Movement of water along these joint planes was evident from the weathering that had taken place along the joint planes and in the adjacent sandstone. In the upper part of this borehole clay films were also present in the joints. Similar jointing was noted in the excavation and in the borehole core drilled in the Arched Culvert Borehole P/IV-6 (see Fig. 5.7). The higher sandstones cored by Borehole R.4 indicated similar joint features. The lower part of the Brithdir Sandstone, some 30 ft thick, is exposed in a quarry 150 yards south of Aberfan Cemetery. This part of the Brithdir Sandstone is equivalent in its position to that which underlies the 'New Spring' of Tip No. 7 and likewise was originally covered by boulder clay. In the quarry the sandstone is a massive current bedded sandstone, extremely well jointed. Three sets of joints are well developed and are well seen in the photographs (Figs. 5.8, 5.9 and 5.10.) They are:

Set A at 34°–38°
Set B at 274°–275°
Set C at 123°–131°

Set A are at angles of 65°–72° to the dip direction and more nearly approach the direction of strike joints.

Set B are at angles of 52°–55° to the dip direction.

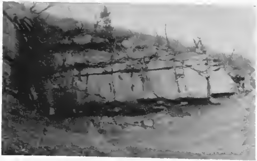
Set C are at angles of 15°–26° to the dip direction and approximate in direction to the trend of the Kilkenny Fault (i.e. 147°–140°).

There is therefore a heavy concentration of joints in this Brithdir Sandstone: two sets B and C are nearer the direction of dip of the beds, and Set A more nearly approaching the strike. Set A is at right angles to Set C. These joint planes as measured in the quarry are inclined at angles between 79° and vertical, and movement of water along the joints can be observed. The spacing or distance apart of the joints shows the following variation:

Set A	10–12 ft
Set B	1½ to 4–6 ft
Set C	6 ft

5.8 Aberfan Quarry south face.

5.9 Aberfan Quarry west face.



5.10 Aberfan Quarry north face

This intersection of joint planes with relatively close spacing of the joints breaks the Brithdir Sandstone up into a series of closely spaced wedges which may be independent of each other, and between which water would readily collect and flow. Deep weathering of the Brithdir and other sandstones with opening and widening of the joint system must have taken place in pre-glacial times. When the glacier entered the valley, frost shattering of the rocks, and later plucking of the solid rocks, took place at the base of the glacier. An example of the action of frost shattering and plucking is provided by the talus debris at the site of the 'New Spring' at Arch 14 in the Culvert (Fig. 5.7).

Samples of Brithdir Sandstone taken from the base of the excavation at Arch 14, and from jointed rock which was considered to be in place by reason of its correct bedding plane dip, were subject to a point count analysis. The following analysis of the rock was made:

Quartz	42%	Detrital materials, 57%
Rock fragments	10%	
Feldspar	5%	
Matrix	43%	Entirely clay, no evidence of quartz or carbonate cement.

From an analysis of total detrital minerals and clay matrix, for four samples the following particulars were obtained:

Total detrital	52·4%	Matrix	47·6%
	53·3%		46·7%
	56·4%		43·6%
	57·0%		43·0%

The coarse grains have a mean size of about 0·2 mm, are generally angular to sub-angular, very few grains show much rounding, and the matrix is wholly clay. The rock is a sub-greywacke, and its porosity is effectively nil. This non-porous rock therefore depends upon jointing for its permeable character.

The Brithdir Sandstone is well known throughout the eastern part of the coalfield as an intensive water-bearing sandstone. Collieries working the Brithdir Seam, pump large quantities of water from these workings. Thus figures from the Trelewis Drift, where this seam alone is worked, indicate that in 1964 and 1965 no less than 611·5 million gallons were pumped in each year. Thus although the sandstone itself has a low porosity due to its heterogeneous constitution it is highly permeable due to the network of open joints and fractures which are produced in this rock by diastrophic forces.

The inference is that the solid rocks below Tip No. 7, i.e. Brithdir Sandstone, consist of a strongly jointed and fissured rock of high permeability allowing rapid access to water through its joint system. The underlying sequence prevents percolation of this water downwards from the sandstone, and the boulder clay cover seals the lateral egress onto the valley side. Water will therefore be stored in the fissures of the sandstone producing a hydrostatic head.

4 Geological interpretation of geophysical survey

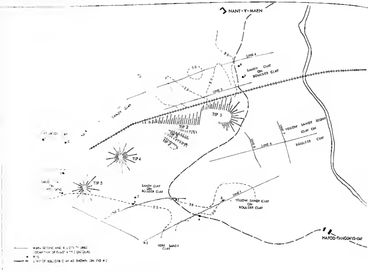
1 *Geological foundations of the other tips*

Part of Tips Nos. 1, 2 and 3 rest on boulder clay; the exact position of the boulder clay boundary is not known but lies somewhere below Tip No. 1.

The solid rocks below Tip No. 1 are rocks below the Brithdir Seam. The toe of Tip No. 2 lies across the outcrop of the Brithdir Seam, otherwise most of the tip is on the Brithdir Sandstone. Tips Nos. 3 and 6 overlie the Brithdir Sandstone. Tips Nos. 4 and 5 overlie the higher sandstone of the Brithdir Beds.

2 *Distribution of superficial deposits*

Fig. 5.11 shows the distribution of the boulder clay and other superficial deposits on the hillside above Aberfan. This plan includes information from surface exposures, borehole information and geophysical


NANT-Y-MAEN
LINE 4
SANDY CLAY ON BOULDER CLAY
LINE 3
SANDY CLAY
TIP 1
TIP 2
TIP 3
TIP 7
TIP 4
TIP 5
YELLOW SANDY STONY CLAY ON BOULDER CLAY
LINE 7
LINE 8
LINE 6
SANDY CLAY ON BOULDER CLAY
LINE 1
LINE 2
YELLOW SANDY CLAY ON BOULDER CLAY
VERY SANDY CLAY
HAFOD-TANGLWYS-ISAF
3.0
2.5
MAIN SEISMIC AND RESISTIVITY LINES
LOGARITHM OF RESISTIVITY CONTOURS
PITS
LIMIT OF BOULDER CLAY AS SHOWN ON FIG 4.2

5.11 Plan showing distribution of superficial deposits

surveys. These provings consist of a programme of soil mechanics' boreholes along and across the slipped area, a geophysical survey around the south, west and north perimeters of the tipping area and a programme of deeper boreholes R.2, R.3, R.4, R.6 and H.G.2 on the south and north sides of the tips.

(i) *Borehole provings*

The soil mechanics' boreholes within and adjacent to the slip showed a surface deposit of yellow-grey sandy stony clay overlying boulder clay. The thickness of this upper clay is variable, ranging from 1½ ft to 7½ ft in thickness and averages about 4 ft. The thickness variation of this clay is random and no variation pattern can be distinguished.

The underlying boulder clay was recorded in all but one of these boreholes, in most cases the full thickness not being proved. In borehole R.2 boulder clay was partly cored from 11 ft to 42 ft, and in borehole L.11 superficial deposits were proved to a depth of 77 ft. Borehole R.3 was not cored, 20 ft of superficial deposits were penetrated which may have been in part boulder clay.

(ii) *Geophysical surveys*

Geophysical surveys were made around the tipping area to delineate the boundary of the clay deposits. Two geophysical methods were used, they are (a) resistivity and (b) seismic.

(a) *Resistivity.* This method measures the electrical resistivity of the materials in the overburden. Traversing was done on the lines shown on the plan (Fig. 5.11) and extended around the south, west and north perimeters of the tips. Twelve pits were dug and the deposits examined so as to calibrate the resistivity readings. Variations in the resistivity values obtained were very large, so, for presentation purposes, the logarithm of the resistivity has been plotted. Clayey material was present in all the pits with the exception of Nos. 3, 10 and 11. It was inferred from this that in areas where the traversing gave a logarithm of apparent resistivity (in ohm-metres) of less than 3·0 the overburden contained clayey material. Thus the position of the 3·0 resistivity contour will broadly delineate the areas where significant quantities of clay are likely to be present.

On the south side of the tips on the lower slopes the 3·0 contour agrees reasonably with the visually mapped boulder clay. Clay deposits, however, extend further up the slope, as a narrow strip lying on the south side of Tip No. 4, and passing under Tip No. 5. Two pits, Nos. 2 and 12, were dug in this vicinity, in both a light grey-brown to yellow sandy clay was exposed overlying a basal clay which resembled boulder clay.

A small area of clay is suggested on the west side of Tip No. 5, two pits were dug here and showed 2–3 ft of sandy clay overlying a clayey sand on rockhead.

On the north side of the tips the 2·5 resistivity contour immediately to the east of Tip No. 6 reflects the outcrop of the argillaceous rocks underlying the Brithdir Seam. Lower down the slope there is reasonably close agreement again between the same contour and the mapped limits of boulder clay.

Three pits were excavated, two (Nos. 10 and 11) north of Tip No. 5 and one (No. 3) some distance south of Tip No. 4. Clayey sand overlies rockhead in the two northerly pits; pit No. 3, however, proved brown to yellow sandy clay.

(b) *Seismic.* The seismic refraction method was employed. In this method a small charge of explosive is detonated at one end of a line of geophones. These geophones record the time taken for the shock waves to travel through the ground. The velocity with which the shock wave travels depends on the material through which it is travelling. From the results the depth to each layer can be calculated. On this site seismic velocities of between 3500 and 5000 ft/sec were recorded in the boulder clay (where known to be present). The top of rockhead was thought to have a seismic velocity of 6000 ft/sec. Depths of rockhead have been supplied on lines 1 to 8 shown on the plan; these figures give the depth shooting into a spread from a particular direction. Boreholes proving rockhead lie adjacent to lines 1, 2, 5, 6 and 7, and the thickness of superficial deposits show close agreement. The average depth to presumed rockhead is 20 ft, various exceptions occur as mentioned below.

On the south perimeter of the tips (lines 1 and 2) the depth to (presumed) rockhead varies from 13 ft to one recording of 54 ft at the extreme western end.

Around Tip No. 5 (line 5) the depth is again variable but rockhead lies close to the surface on the west side of the tip.

On the north side of the tips (lines 3 and 4) great variations in depth are recorded ranging from 14 ft on the upper part of the slope to 61–70 ft lower down. The quality of the records from these seismic spreads, however, is poor. A few boreholes have been sunk near the line, these show the depths to rockhead is not as great as that shown by the Geophysical Survey. The information obtained from borehole H.G.4 suggests that the rocks are highly jointed and are self-draining. Such a condition would explain the recorded anomaly.

Within the slip area, line 6 is aligned along the slip whilst lines 7 and 8 are transverse to the main line of the slip. Along line 6 the readings are variable and with the exception of a depth of 50 ft recorded where line 7 intersects line 6, the depths to rockhead range from 13 to 27 ft. Line 7 shows depths of 43–58 ft across the main line of the slip. Line 8, which lies north of line 7, does not show similar depths (18–34 ft).

The following significance can be attached to the variations of depth to rockhead. On line 1 up the hillside the variations in depth appear to be random; one deep record of 50 ft at the extreme west end of the line appears to be very local as does the 43–44 ft in the vicinity of R.2

borehole. The thicker superficial deposits clearly fill depressions in the rockhead. On line 2 alongside Tips Nos. 4 and 5 the depths range from 18 ft at the uphill end to 30 ft down the slope. On line 5 which extends around Tip No. 5, variable depths are again present on the south side; along the west and north sides rockhead is shallow, becoming deeper down the slope. The anomalies shown on lines 3 and 4 have not been substantiated by borehole proving. Line 6 extending down the line of the slip shows depths averaging 20 ft or just under. One depth of 50 ft is, however, present which taken in conjunction with those recorded on line 7 across the slip area shows the presence of a more extensive area of deeper rockhead, an infilled tributary valley.

The following inferences may be drawn:

(1) The yellowish varicoloured sandy clay which contains sandstone fragments, cobbles and boulders extends high up on the hillside and is quite extensive in distribution. It is variable in thickness, the maximum proved where analysing boulder clay being 7 ft; however, the depth to rockhead recorded above and beyond the limits of the boulder clay show that greater depths of this type of deposit must be present on the hillsides.

(2) On the upper platforms formed by the outcrops of the Pennant Sandstones a more sandy deposit is present.

(3) Even with all the proving which has been done it is difficult to define the exact spread of boulder clay on the hillside. It certainly extends up to the limit shown on the Geological Map. The material examined from Pit 12 resembles boulder clay and it may be that patches of boulder clay extend high up the valley side. Such a distribution can be expected where a tributary valley contained a lobe of ice as this one did in the Ice Age. The Taff Valley ice probably only extended up to the approximate limits of the boulder clay as shown, but local ice, feeding from a small snowfield near the top of the mountain, may have occupied the upper part of the valley, forming its own ground moraine.

V HYDROLOGICAL CONDITIONS UNDER TIP NO. 7

The Brithdir Sandstone has been shown to underlie Tip No. 7, and by reason of its mineralogical composition demonstrated to be a non-porous rock. By reason of the geological structural effects to which it has been subjected it is a jointed and fissured rock with high permeability, both along its outcrop and as proved in mine workings. The seatearth which underlies the Brithdir Seam is of a clay nature as are the mudstones which underlie the seatearth. These rocks form an impermeable seal which prevents the downward percolation of water from the joints in the Brithdir Sandstone. Samples of the sandstone have been tested for permeability and the results of the tests are included in Table 2.

To the north and north-west of Aberfan the Brithdir Sandstone outcrops on the valley side and across the top of the northern end of Mynydd Merthyr to form an extensive catchment area. Rainwater falls on this catchment area and as described in Section II of this Report, part of the rainfall forms 'run off' water, part evaporates, and part enters the rock to form groundwater. The distribution and movement of this groundwater is governed by the characteristics of the rock and by geological structure. Since the rock is non-porous, water can only enter the rock by the joints and fissures and will thence flow down the dip or slope of the bed in these fissures. The prominent dip joints in the rock, i.e. Sets B and C in particular, will aid this flow which will thus be rapid, and Set A joints will serve as interconnecting links between the dip joints. The water is thus carried down the dip in the open joints and fissures. Under normal circumstances where the Brithdir Sandstone is dipping and its base and the underlying impervious solid rocks are exposed there is egress of water as seepages along the outcrop of the base of the sandstone. At points where the strike or Set A joints are open and present at the base of the sandstone, water may issue through the joint at the surface as a small spring. This normal condition is present to the north of the tip complex where only one spring of note and gentle seepages are observed at this basal junction of the Brithdir Sandstone with impermeable solid rocks consisting of fireclay and shales.

The abnormal condition is provided within the area of the tip complex and to the south thereof. There the base of the sandstone, and in the region of the tip complex a considerable part of the sequence of the Brithdir Sandstone, is concealed under a cover of impervious boulder clay which would effectively seal up the water contained in the joints of the sandstone. This restriction of outlet will cause the water to fill up joints and fissures and build up a hydrostatic head. Thus the water is contained in the joints and fissures in the body of the sandstone, and depending on whether the joints are open or closed what may be referred to as a very localised joint 'water table' or fissure system water table will be present. The interconnected nature of the joint systems described illustrate the propensity for a hydrostatic head of water to be built up under conditions where the joints are open, and there is free movement of water between and within joints. Any outflow from an area concealed by boulder clay would be limited to weak points in the boulder clay, or to places where open and unsealed joints still remained.

Such a localised fissure system containing water in the area of Tip No. 7 can be demonstrated by a comparison of the evidence of water levels in the recently uncovered 'New Spring' at Arch 14 (Fig. 5.7) with that in Borehole R.2 (Fig. 4.2) outside and to the south of the confines of Tip No. 7.

The surface level of the 'New Spring' at Arch 14, which was first seen to be flowing on 21st October 1966, is 818·8 ft A.O.D. Borehole R.2, which lies 190 yards away (see Section E–F (Fig. 4.4)), was almost completely dry although the sandstone cores were well jointed. The water from the vicinity of Borehole R.2 is probably drained away through old workings proved in the borehole, to emerge at river level at Perthigleisian where its volume was measured at 900–1100 gal/hour between 17th and 18th November 1966. This yield should be compared with the greater and more fluctuating yield from the 'New Spring' of 780–3180 gal/hour.

The surface level of the Borehole R.2 is 836 ft A.O.D., and the level of the base of the old workings proved was 714·8 ft A.O.D. The Borehole P/IV-6 at the site of the 'New Spring' at Arch 14 commenced at 818·2 ft A.O.D. and tapped water with a small hydrostatic head.

These facts prove that although the joint pattern of fracture is well developed not all the joints are open and thus not totally interconnected. Local reservoirs of water with their own individual hydrostatic head can build up within open fissures where the outlets of such fissures are sealed off. As referred to in Section II of this Report, movement of the jointed rock under the influence of gravity, by localised subsidence, or by differential subsidence on a regional scale could effect the disposition of the jointed sandstone blocks, opening up the joints in places.

From the figures of water flow for the 'New Spring' (see Table 1 and Fig. 5.6) and from the account presented in Section II of this report it is clear that groundwater in a fissure system was dammed up in the Brithdir Sandstone beneath the impermeable boulder clay and head cover under Tip No. 7. Indeed since the Brithdir Seam lies at an approximate depth of 76 ft below the 'New Spring' there still remains a reservoir of water with a potential head of 76 ft dammed up behind the boulder clay. The 'New Spring' is acting as an overflow for this body of water. Its rapid fluctuation, closely related to rainfall, is only in part a measure of the additional water entering and being released from the system by the restricted outlet. It is not, however, a measure of the total water entering the system. This may well be in excess of the release and the water in the fissure system will continue to build up at periods of heavy rainfall, when the intake exceeds the release at the 'New Spring'.

Fig. 5.7 illustrates in section and plan view the particulars of the Arched Culvert constructed after the failure of Tip No. 7. The floor of this culvert has been explored by the digging of a pit and by a borehole. Broken sandstone was intersected by the borehole, and a talus deposit of large angular blocks of sandstone form the floor; these blocks are cemented by infillings of sandy clay, and in places lenses of yellow clay occur between the blocks. At the head of the culvert a section of yellow sandy clay overlying the basal talus is present. This clay was either removed from above the talus over the culvert floor by the action of the slip when the tip failed, or was removed by the water outburst which occurred.

When this culvert was first seen by the National Coal Board geologist on Sunday, 23rd October 1966, water was issuing from the floor at several points and from a deposit of yellow sandy clay which contained stones and boulders. This issue was at Arch 7. Subsequently the flow reduced and the hydrostatic head fell so that the point of emission migrated to Arch 14, and then to Arch 24. At its lowest point of issue and lowest yield the main egress of water took place at Arch 32 on 7th November 1966. Following upon rainfall, the flow increased and the issue migrated back to Arch 14. A similar migration of the spring has taken place between Arches 1 and 27 during the period from 31st December to 9th February 1967. The spring response to rainfall took place within two days, and indicates the rapid speed of intake of water into this localised water system from rainfall. Drilling at Arch 14 has intersected the fissure system and released more water with a hydrostatic head.

Thus over the observed time period and from the observations made above there has been a total fall in the level of the water held in the Brithdir Sandstone of 824·4–810·2 ft, i.e. of 14·2 ft and a subsequent rise from 810·2 ft to 818·8 ft, i.e. of 8·6 ft. More recently following a period of heavy rain the head of water in the inclined borehole drilled to the end of the Arched Culvert was measured as 14 ft. On that day the water level in the Brithdir Sandstone was 826·6+14 ft, i.e. 840·6 ft. The rise in level of water in the system has taken place despite the release of water by spring flow, proving the intake over that period to be in excess of outflow. Such facts clearly demonstrate the underground source of the water, and the rate of rise with the present outflow suggests the possibility of far greater total rise of water level within the sandstone when the exits for water now seen in the culvert were sealed off by the clay cover.

The 'New Spring' site at Arch 14 was excavated to a depth of 4 ft in material which consisted of angular blocks of sandstone cemented by infillings of sandy clay. The clay overlying this talus is probably the weathered wedge of the boulder clay and percolation of water within it or a rise of the water level such that it overflowed the edge of the boulder clay, would cause water to enter the deposit, so weakening its structure. Alternatively the water could overflow the boulder clay and enter the base of the tip and issue as a flow or seepage at the base of the tip and over the upper surface of the boulder clay.

The open joints in the Brithdir Sandstone have been observed in borehole cores and in quarry exposures, and rapid discharge of water held in these joints once an outlet is made has been demonstrated. Equally it has been proved that such joints rapidly fill up with water after rainfall. The Kilkenny Fault is shown to be closely associated with the direction of the joint systems. As a major fault affecting thick beds of sandstone it will itself almost certainly carry water and will allow migration of groundwater from higher sandstones to percolate into the lower beds and thus effectively increase the catchment area available to its down thrown side. The section E–F (Fig. 4.4) illustrates this potential.

The total volume of water estimated to have issued from the main source after the failure of Tip No. 7, between the dates of Friday, 21st, to Monday, 24th October 1966, is calculated as 18,500,000 gallons or 109,200 cubic yards. Assuming a void percentage of 8% (i.e. 3 in. per yard) the volume of sandstone required to store this amount of water is 1,310,400 cubic yards. Assuming the Brithdir Sandstone to be no more than 100 ft thick (33 yards) then this volume of water would be carried in the fissures of an area of sandstone 100 yards long by 400 yards wide—a very small area compared with the total available expanse of Brithdir Sandstone.

The inferences to be drawn are:

(1) The Brithdir Sandstone under Tip No. 7 is permeable and fissured and carried much water in joints and fissures.

(2) This water is groundwater and shows a two-day response to rainfall, therefore the fissure system is large and open.

(3) Not all joints in the sandstone are open and it has been shown that localised reservoirs of groundwater are built up in joints and fissures with a hydrostatic head where natural outlets are blocked or sealed.

(4) One such localised reservoir built up below the boulder clay cover underneath Tip No. 7. When breached a large discharge of water took place.

(5) Water with a hydrostatic head still remains in this reservoir.

The underground water level in the Brithdir Sandstone has been shown to rise and fall, and this is demonstrated by the migrating position of the spring outflow in the Arched Culvert. There is for this spring an established period of two days delay between the end of heavy rainfall and a rise of the water level. An abstract from the Meteorological Office Register of Rainfall Figures for the rainfall in inches per day is given below for the period 14th to 20th October 1966 prior to the failure of Tip No. 7.

Record at	October						
	14	15	16	17	18	19	20
Penbryn Filter Beds (Merthyr)	·96	·10	·09	·56	*1·22*	*1·23*	·03
Treharris Reservoir (Glam.)	·91	·19	·04	·25	*1·03*	*1·80*	·01
Mountain Ash (Glam.)	1·01	·01	·14	·49	*·86*	*1·89*	·07

The very heavy rainfall of 18th and 19th October 1966 was effectively completed on the latter date and the failure of Tip No. 7 took place on 21st October 1966. This is the two-day period of delay between rainfall and spring flow already demonstrated for the spring in the Arched Culvert. The inferences are therefore:

(1) That the large volume of water which flowed from Tip No. 7 commencing on 21st October 1966 shows the same time delay relationship with rainfall as does the present flowing 'New Spring'.

(2) The large outflow of water on 21st October 1966 was derived from the same source of groundwater as that still flowing from the 'New Spring'.

(3) The volume of water and its rapid discharge indicates a very high rise of the groundwater level, with high hydrostatic pressure built up in an extensive fissure system under the mountainside. This water probably came up through an open dip joint.

(4) This volume of water did not come from a surface source direct.

Water flow details

Details of the water flow from the region of the culvert are presented in Appendix I to this Report (not reproduced here, see note in Contents).

On Friday, 21st October 1966, at 1300 hours D. Bowen estimated the flow from the main issue to be 400,000–500,000 gal/hour.

The water was issuing as mudflow from approximately 10–15 ft up the face on a width of approximately 30 ft. This would be in fact from a position above the line of junction of the boulder clay and the tip material. Whether or not water was also being discharged from the bottom of the slip could not be seen.

On Saturday, 22nd October 1966, at 1650 hours P.M. Grant estimated the flow at 234,000 gal/hour, the water issuing as a clear stream from the bottom of a 7-ft wall of clay.

On Sunday, 23rd October 1966, two estimates were made from the main source:

At 1550	100,000	D. Bowen
At 1600	130,000	P. Grant

At this time the water was seen to be discharging from a number of points across a width of about 8 ft at the bottom of an exposure of clay 4 ft thick. This type of emission suggests egress along the line of one of the major dip fissures.

The above record emphasises an original high head of water, the level of which fell between Friday, 21st October, and Sunday, 23rd October 1966 and which has continued to fall as the water level was reduced by outflow.

The further particulars have already been referred to but they are repeated here for completion of the record.

On 27th–28th October 1966 the water flow issued at the 'New Spring' at Arch 14 at 818 ft A.O.D., i.e. 6 ft lower than the source observed from the floor at Arch 7. Subsequently the source fell to Arch 24 at 816 ft A.O.D., and finally to Arch 32 at 810 ft A.O.D. on 7th November 1966. The flow increased and the source migrated back to Arch 14 as a result of rainfall on 5th November 1966. The level of issue had thus fallen a total of 14·2 ft between 23rd October and 7th November 1966, and subsequently rose 8·6 ft back to its present source of issue. At Arch 14 a head of water was measured during the drilling of a borehole as 4 ft on 21st November 1966 which placed the water level at 822 ft. The analyst is of the opinion that the chemical characteristics of the water indicate it to be probably natural groundwater and that the constant temperature corroborates an underground source.

1 Additional evidence concerning hydrological conditions under Tip No. 7

A *Evidence for fissures in Brithdir Sandstone*

(i) *Borehole P/IV-6, No. 2 in the Arched Culvert* (N.C.B. Hole): passed through 79 ft 9 in. of Brithdir Sandstone, through the position of the Brithdir Seam and intersected 50 ft of mudstones with occasional seatearths and siltstones. The borehole demonstrated the impermeable nature of the strata below the Brithdir position. The cored Brithdir Sandstone, throughout its thickness, was jointed—the inclined joint surfaces were visible in the cores and were stained and weathered by the passage of water. The bedding planes were likewise weathered and stained. Between 50 ft 2 in. and 58 ft 7 in. brown sand was associated with the borehole cores and was thought to be material in part washed into the borehole by water flowing through joints and fissures.

(ii) *Inclined borehole—head of Arched Culvert* (N.C.B. Hole): Commencing at the head of the Arched Culvert and at a point where the boulder clay underlying the tip is visible, a borehole inclined downwards at 30° to the horizontal was driven under the tip, for a distance of 121 ft 8 in. This borehole driven approximately west continues the line of direction of the Arched Culvert. Summarily the evidence provided is:

(1) Boulder clay: talus material to 10 ft 3 in.

(2) Sandstone: to 62 ft 2 in. The sandstone was cored between 16 ft and 47 ft 8 in. and during this operation penetration by the drill of 24 ft 5 in. yielded only 7 ft 9 in. of recovered core, indicating broken or jointed rock, or badly weathered sandstone. Gaps of 3 in. were recorded between 56 ft 4 in. and 56 ft 7 in. and again between 59 ft 1 in. and 59 ft 4 in. The gaps represent very rapid advance of the drilling bit and are due to fissures or very soft weathered sandstone.

(3) Below 62 ft 2 in. similar gaps of 5 in., 9 in., 7 in., 5 in. and 4 in. are recorded by the drilling log in rock recorded as mudstone.

(4) The borehole was dry down to 60 ft and there was no return of drilling water. At 88 ft water under hydrostatic pressure was tapped and flowed out of the borehole, and has continued to do so. On 23rd February 1967 a head of 12½ ft was recorded on a measuring gauge.

The evidence is thus conclusive, the sandstones are fissured and water under a hydrostatic head underlies the tip in these fissures. The evidence corroborates the fissure rise and fall of the outflow in the Arched Culvert.

B *Effect of mining subsidence*

The joint system in the Brithdir Sandstone represents original structures related to the Kilkenny Fault and the early geological history, and were as joints present long before mining subsidence affected the Aberfan area. Piggott and Wardell in their Report on Mining Subsidence to the Tribunal (Item 6) refer to both vertical and horizontal components resulting from mining subsidence, and one expression of these movements is to be seen in the open fissures on Mynydd Merthyr. These visible fissures follow very closely the direction of the dip joints, and mining subsidence has activated movement along these lines. This is particularly noticeable on the flanks of the large compressional zone of subsidence on the south side of the tip complex.

By reason of an unworked barrier of coal the authors indicate a narrow zone of tensile strain underlying Tip No. 7 and which is flanked by a major region of compression to the south-west and a small zone of compression to the north-east. The effects under Tip No. 7 would be to open up the dip joints running through this area, creating fissures in the Brithdir Sandstone. These fissures would not necessarily be visible at the surface since the cover of boulder clay and superficial material would conceal them and the softer material accommodate itself to the underlying structure. Water would be admitted to this area through the joints from up dip regions to the north and north-west and would be channelled into the area of Tip No. 7 along the line of predominant fissures.

The area under Tip No. 7 forms part of a glacial side valley in which weathering of the rock and jointing would have been normally well established. The superimposition of tensile strain by mining subsidence on such pre-existing conditions would have maximum effects in fissure formation.

Piggott and Wardell consider the compression zones by reason of their closed joints to have restricted the outlet of water from the area of Tip No. 7 in an eastward and particularly in a southerly direction. In this manner they consider an accumulation of water was built up in the open joints under Tip No. 7 with a considerable pressure head. Whilst this is possibly a contributory factor it would not appear to be the main factor which resulted in the build-up of water under Tip No. 7.

C *Boulder clay seal*

Reference has been made in the report to the irregular base of the boulder clay cover, and to the possibility that this infills a tributary valley or valley system.

On the south side of Tip No. 7 borehole R.2 proved the thickness of the boulder clay to be 43–44 ft. A later borehole (Treasury Borehole

L.11) midway between R.2 and the 'New Spring' has proved a total thickness of superficial deposits to be 77 ft well in excess of any other recorded depth. Borehole Treasury L.9 proved superficial material to between 45 ft and 59 ft; the precise depth to rockhead could not be established in view of the talus occurring at the base of the boulder clay.

These thick superficial deposits substantiate the original indications of the infilling of a buried valley system the detailed pattern of which is not known. These deep sections of superficial deposits are cut down into the Brithdir Sandstone, at one position very near to that of the Brithdir Seam itself. The superficial deposits would prevent or certainly restrict the normal down dip circulation of water from the area of Tip No. 7. This in turn would result in a build-up of water in the fissures under that area and account for the hydrostatic pressure and head of water.

VI GEOLOGICAL EVIDENCE AVAILABLE AFTER FAILURE OF TIP NO. 7

1 Slipped material

The disposition of the slipped material apart from the 'mudflow' in the central part of the slip shows the material to have been largely floated down the hillside as a fluid mobile layer which now rests on the original turf and soil, above the boulder clay and other deposits. Little if any rolling of the material appears to have taken place. Some physical removal of the underlying clay occurred locally, and notably nearer the foot of the tip; this clay can be seen as lumps of yellowish clay included amongst the slipped material. Erosion of the clays took place in the excavated stream channel, and boulder clay is exposed in the bed of the stream at several points, the highest is some 150 yards downstream from the 'New Spring'.

2 The lower slip face

A semi-circular slip face of tip material facing east lies immediately above the 'New Spring'; the walls of this face slope at an angle of 37°. On either side of the Arched Culvert, which reaches this face, the original soil level containing rootlets is visible and is underlain by 4 ft of yellow sandy clay. Upon the surface of the soil the tip material is present. On 2nd November 1966 water was seeping from the junction of the tipped material and soil. The Arched Culvert has been cut back into the tip for a short distance beyond the point where spring water was observed to issue from yellow sandy clay on 23rd October 1966, i.e. Arch 7 (Fig. 5.7). On 2nd November 1966 water was still seeping out between the tip material and the clay in the face of the first Arch 1.

3 The Arched Culvert

The Arched Culvert (see Fig. 5.7) was erected over the upper reaches of the stream issuing from the 'New Spring'. Its upper end carried a protective cover for the section of yellow sandy clay containing angular rock fragments which rests upon the talus material of the floor. This talus material at the upper end of the culvert is extremely coarse; blocks of angular material as much as 3 ft × 1 ft 6 in. × 2 ft were measured, and these lie at variable angles and are cemented by clay, in part sandy but in other places soft and tenaceous. The position of the boulders give a stepped profile in the upper reaches of the culvert. The gradient of the culvert is shown on the plan and section, it is steeper at $27\frac{1}{2}°$ (1 in 2) at the upper end and grades down to $13\frac{1}{2}°$ (1 in 4) at the lower end. This gradient represents either the normal curve of water erosion, or maybe the surface of a slip plane which was controlled by the hard talus layers forming the basal section of the boulder clay. From Arch 14, the present position of the 'New Spring', for a distance of 13 yards the stream flows over angular stones and boulders which again lie at various angles and are cemented together by clay. Along this reach of the water flow the volume increases as a result of other feeders emanating from the basal talus.

The evidence from the upper part of the culvert suggests that 8 ft or more of the overlying clay has been removed down to the harder talus material, either physically as a result of a slip or by water erosion, or by a combination of these methods. At Arch 14, on the site of the 'New Spring', an excavation 4 ft deep was made. The material removed consisted entirely of angular blocks of sandstone. In the borehole at this point cores of the top 6 ft of rock were not recoverable, and this may indicate the depth of the talus at this position, or the presence of highly weathered rock head. The borehole encountered considerable drilling difficulties in broken sandstone and had to be abandoned at a depth of 52 ft having proved weathered and jointed sandstone to this depth. A second borehole was commenced a yard distant but drilling had stopped while remedial measures relating to tip safety were in progress.

4 Details of tipped material and standing faces

The tipped material is heterogeneous and consists of some run of mine waste, with much washery discard together with, on the immediate east side of the tip, a certain amount of tailings. In size the material ranges from very small, to blocks about 1 ft in size; the bulk of the material is 4 in. or less. The rock consists dominantly of argillaceous mudstones and shales frequently carbonaceous, with silty mudstones, seatearth and ironstone nodules. The dominant clay minerals in the shales are those characteristic of Coal Measures sediments, i.e. kaolinite and illite and some iron pyrites is present. Chemically most Coal Measures shales are characterised by a silica (SiO_2) content, either free or combined, which ranges between 45% and 60%, and alumina (Al_2O_3) is the next largest constituent, ranging from about 20% to 40%. Iron content is variable and there is normally low calcium, magnesium, sodium and potassium content which are often less than 1% and seldom as high as 3%.

The larger rock materials on the tip are angular blocks, but the fragments from the washery discard have been sub-rounded in the washery processing and have carried on to the tips some of the chemicals used in the washery. The larger material is in reasonably fresh condition and there is little evidence of heavy chemical weathering. The presence of a white efflorescent deposit of sodium sulphate indicates the atmospheric oxidation of iron sulphides, to produce sulphuric acid which combines with the sodium in the shales to produce the sodium sulphate (see Evidence of Analyst, Appendix Ib of Report).

A *Top feature*

On the north side of Tip No. 7 the highest slip faces slope at angles of 31°–35°, whilst on the west side a steeper face is present with a slope of 50°–55°. Slopes with a gradient of 31°–35° may be the original tipping slopes, for they are present as dried and continuous bedding planes of slurry material which are undisturbed. The steeper slopes represent a shear plane in finer material and show faint evidence of slickensiding.

B *Middle feature*

The intermediate feature is formed by a massive semi-circular ridge of material facing east. This ridge slipped sideways and inwards from the outer rim of the tip towards the centre following the earlier removal of material from the toe and centre of the tip. The inner slopes of this foundered ridge vary from 32° to 43°.

C *Basal feature*

The semi-circular slip face immediately behind the head of the Arched Culvert has already been described (Section VI.2).

5 Water feeders from tip material

Following the slip of Tip No. 7, on 21st October 1966, two distinct streams were present draining the slipped area. They were:

(i) The stream derived from the succession of issues found in the Arched Culvert and which had a very high initial flow and subsequently decreased. Feeders from the tip material contributed to the flow of this stream and several such feeders can still be observed in the lower part of the Arched Culvert. Lower down the slopes this material received some drainage from the tip material, which appears to be self-draining.

(ii) The stream draining the south side of Tips Nos. 1, 2 and 3, a stream which was previously present and has continued to flow. This stream is fed by a number of springs which are marked as the water sampling points (Fig. 5.5). The source of the stream is a spring at sampling point No. 5 and a substantial spring is present at sampling point No. 7. A further spring was present at sampling point No. 6, on 29th October 1966. Originally the water in the upper two springs issued from tip material whilst the water from the sampling point No. 7 appeared from the junction of the slipped material upon the turf and soil. All these springs have recently been excavated and the water can be seen issuing from a boulder clay 'head' deposit.

A further new spring was observed at sampling point No. 3, a short distance east of the toe of Tip No. 1, the water welling out of a hole in the ground and flowing away over the turf. It was subsequently proved that much of this water was derived from the small stream which flows on the north side of the haulage incline. The water from the Arched Culvert is now diverted into the stream course that flows on the south side of Tip No. 1, and the total combined flow is measured at a V notch on the side of the canal. The flow of this V notch (V3 in Fig. 5.5) therefore represents the total flow of water from the Central Complex. On 22nd November 1966 this flow was just over 19,000 gal/hour compared with 2,000 gal/hour denoted as V6 and separately recorded from the source within the Arched Culvert. On 1st December 1966 the recorded respective flows were:

V3 80,000 gal/hour
V6 22,000 gal/hour

The chemical analyses of all these waters have been referred to in Section II.3 of the Report; they are all similar and suggest a common origin. The inference follows that both streams are fed in the main from water emanating from the Brithdir Sandstone, and follows the observations made in Section II.2.1 of this Report concerning the withdrawal of the headwaters of almost all the streams on the hillside in the neighbourhood of Aberfan. That this water is in places contaminated by leaching from tipped material is understandable.

VII CONCLUSIONS

There is a series of closely related factors which are interdependent upon one another and additive in their total effects. These enable the following conclusions to be reached:

(1) The primary cause of the failure of Tip No. 7 was geological in character. There was a coincidence of a set of geological factors each of which in itself is not exceptional, but which collectively created a particularly critical geological environment. The factors are:
   (a) The regional effects of mining subsidence in admitting a higher proportion of rainfall as groundwater into the rocks, creating a rise in the level of the groundwater. This also resulted in the retreat of streams on the hillside—a feature common to mined regions.
   (b) The sequence of rocks—permeable bedded sandstone underlain by impermeable strata—preventing the downward passage of groundwater.
   (c) The jointed character of the sandstones originally related to the tensional effects of the Kilkenny Fault, later affected by ice, and reactivated and opened by mining subsidence; the joints also liable to opening by the down dip gravity movements of blocks of sandstone at the edge of outcrop on a steep valley side.
   (d) The development of a proved fissure system containing water, the system being extensive and open and showing unusually rapid response to rainfall, and continuing still so to do.
   (e) A catchment area for groundwater which is potentially extensive and is thus a geological controlled catchment dependent on structure. The unusual amount of water from the tip complex area indicates this.
   (f) The region is a pre-glacial structure, a line along which springs or tributary streams formed a side valley. This region was later affected by ice and infilled with glacial material which reaches to an unusual height on the hillside.
   (g) The boulder clay seal on the sides of the valley and under Tip No. 7 prevents the normal egress of water by springs or seepages.
   (h) Deep buried channels infilled with boulder clay, cut down into the Brithdir Sandstone and restricts or prevents the escape of water from under Tip No. 7 in a down dip direction southwards.
   (i) The presence of a large zone of mining compression on the south side of Tip No. 7 may contribute to the effects of (h).
   (j) The presence of a barrier in the deep workings under Tip No. 7 creates a narrow zone of extensional strain which opens the joints and increases the potential for water flow and collection below Tip No. 7.
   (k) The total result is to build up a level of water in the sandstones below Tip No. 7, which has a considerable hydrostatic head. The pressure may be such as to move blocks, or force a passage through the boulder clay seals—with rapid escape along fissures.
   (l) The presence of impermeable boulder clay and superficial deposits, the clay soft and plastic, its mineralogical and physical constitution being such that a*dsorption* of water results in a reduction of strength eventually to the point of plastic flow.
   (m) Clay on steep slopes is naturally unstable and shows surface creep and flow and is seen in this condition on the hillside; the tendency to movement will be increased by loading.

(2) There was consequently a rise of the water level in the open fissures of the Brithdir Sandstone which created a hydrostatic head of groundwater. Either one or both of the following alternative circumstances would have arisen from this accumulation:
   (a) The water level rose in the Brithdir Sandstone to such a height that it overflowed the thin feather edge of the boulder

clay. This interpretation is substantiated by the evidence of water issuing in great volume from the tip material and above its junction with the underlying clay on 21st October 1966, and along a line 30 ft in length.

(b) The hydrostatic pressure rose as a result of the increased water level and to a point high enough to penetrate and break through the thinner patches of clay, or clay seals in the sandstone talus which forms the base or is near the upward limit of the boulder clay extent. This point is substantiated by feeders of water seen to issue from the base of a 4 ft section of stony and sandy clay on Sunday, 23rd October 1966.

(3) No evidence has been obtained to suggest that other factors were involved, e.g.:

(a) The Brithdir Seam has not been worked under the tip, and it is considered that subsidence of old workings on the south of the tip would have been complete and did not affect the failure of Tip No. 7 (see Piggott and Wardell).

(b) There are no known seismic effects, e.g. such as earth shocks, or renewal of movement on fault lines which may have affected the stability and equilibrium of the jointed rocks. Any movement, e.g. gravity slip, or movement induced by surface loading, which destroyed the equilibrium of the existing fissure drainage system may have introduced a new and additional head of water at a time of intensive rainfall, and a more spontaneous eruption of water would take place.

(c) The example of Craig Abercwmboi, 1960 (Appendix III), where a large volume of water burst from the hillside after heavy rain is a case in point. Here the water issued from fissured sandstone above the outcrop of the No. 1 Rhondda Rider. These sandstones were continued in a narrow belt between two faults, the Gadlys Fault (300 ft) and a small fault (20 ft), both downthrowing to the south-west. Water burst out along the line of the smaller fault which was by tensional effects of throw and by mining subsidence presumably open and acting as a fissure. The sandstones were sealed by head and boulder clay in a similar manner to those under Tip No. 7. At Abercwmboi shallow workings in the coal seam had taken place, but a barrier of coal was left to the outcrop, which was not broken through, since the water burst followed the line of the fault. An additional head of water during heavy rain entered this system, and forced its way into the seal of boulder clay and head. The failure of the sealing material led to the rapid outburst of water. It is to be noted that the line of the Abercwmboi outburst is one at which landslips have previously occurred, and the seal may have initially foundered by land slipping which thereby released the water. Such a circumstance would be analogous in action to that under Tip No. 7. A further example of this type occurred in fissured permeable limestones of Derbyshire on 3rd April 1966 after heavy period of rainfall (see H.M. Parker, 'Explosion at Magpie', *Derbyshire Caving Association Newsletter*, Vol. 5, September 1966). As a result of a fall of rock in a water course in the lead mine, the fissure water built up to a high head and poured out of the hillside at numerous places. Finally the water burst out of an infilled air shaft, blowing out a 30 ft crater and depositing hundreds of tons of limestone and shale over a wide area and creating a new stream cutting through the debris. The water is said to be pouring out of the crater at an alarming rate.

These instances may be regarded as special circumstances, but in heavily jointed and fissured rock, disturbance of equilibrium conditions can have rapid effects.

(4) The effect of either alternatives listed, 2(a), 2(b), would be to admit water into the base of the tip material and on to the weathered surface of the boulder clay. This admission of water commenced from a point within the tip, near the uphill limit of the boulder clay material beneath the tip. This is from a point at least as far within the tip as the head of the Arched Culvert and may have been some 10 ft uphill of this, as suggested by the boulder material in the inclined borehole. This borehole also proved fissured sandstone, with significant gaps interpreted as open fissures or very heavily weathered rock which may have been the original source of emission from the Brithdir Sandstone. Water would thus percolate towards the outer and lower surfaces of the tipped material.

(5) The presence of this water would increase the mobility of the tipped material, reduce its internal frictional resistance, and the frictional resistance between the tipped material and the boulder clay. The plasticity of the boulder clay would be increased by the physical process of water *adsorption* (i.e. addition of extra layer water to the clay mineral lattice) and its strength thereby reduced.

(6) Failure of the tip was due to instability at the junction of the tipped material and the underlying boulder clay, or within the boulder clay under the conditions existing and on the particular slope and degree of loading.

(7) Consequent upon the movement of tip material which stripped away some of the boulder clay cover and at the same time may well have caused movement of the sandstone blocks, there was an increased water break from the fissures in the Brithdir Sandstone. The rapid discharge of the great quantity of water from this source converted the already slipped and slipping material into a mudflow which flowed as a central stream of mud down the hillside and into the village. Aerial photographs taken at 1300 hours on 21st October 1966 show clearly the differential flow features in this channel. Material moved down the hillside leaving a valley averaging 70–80 ft wide with walls of tip debris standing 15–20 ft high. This part of the sequence of events is analogous to mudflow in recorded landslips from many parts of the world.

Report on Mining Subsidence

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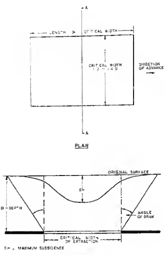
1 During the last 20 years, mining engineers and surveyors in Europe have made intensive field studies of the subsidence effects caused by the underground mining of coal. Observation points have been laid down, at suitably spaced intervals, across surface areas which were to be undermined. As such mining progressed, the subsidence of these points was observed by precision levelling and the distances between adjoining stations were measured, also with precision, to determine the horizontal movements of the ground surface. The observations were made with sufficient frequency to enable time effects to be studied. Records of seam thickness, depth, gradient, rate of advance, method of filling or packing the worked out areas and the geological sequence to the overlying surface were kept to assist in correlating observed surface effects.

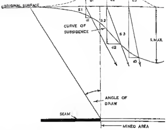
2 A mass of observed data has been accumulated by these methods which covers a wide range of physical and geological conditions and from which some common principles covering the mechanics and development of surface ground movement have been deduced. There is, as yet, no unifying theory but rather some empirically deduced principles which enable surface ground movement to be described and predicted in terms of simple dimensional parameters such as seam thickness, depth, dimensions of extracted area, method of packing etc. These principles have proved to be common to all European coal-mining areas and even to extend to the mining of other stratified minerals. Needless to say, the absence of a comprehensive and unifying theory means that quantitative values for the dimensional parameters have to depend on local observations. Where these are available predictions related to mining a single seam can be made to an accuracy in the order of ±15 per cent. Where prediction involves the aggregation of a series of separate calculations in respect of several seams, accuracy falls off and the results of such calculations tend to become broadly qualitative rather than quantitative.

3 The surface ground movements above and around an area from which coal has been extracted are simplest in form in their final development, transverse to the direction of advance as shown in Figure 6.1. It is always observed that the final subsidence is in the form of a trough or basin with its deepest point over the worked-out area.

4 Subsidence extends beyond the limits of underground mining and the angle between the vertical plane over the edge of extraction and the line joining the perimeter of underground mining to the perimeter of surface subsidence is called the angle of draw or limit angle. Its observed value in British coalfields normally falls within the range of 30–40°.



6.1 Diagram showing development of maximum subsidence over working area of critical dimensions



6.2 Diagram illustrating direction of movement of surface points and their vertical and horizontal components.

5 The subsidence at the deepest point of the trough or basin only reaches a maximum when the width and length of the extracted area concerned exceed certain critical dimensions. These dimensions in British coalfields normally fall within the range of 1·2 to 1·4 × the depth of the seam worked. When the mined-out area is in excess of these critical dimensions, the maximum final subsidence is then simply a function of the thickness of the extracted seam and the method of filling or packing the worked-out area. When caving (or no packing) is employed maximum subsidence is normally about 90 per cent of the seam thickness. If regular packwalls are constructed in the mined-out area from broken roof material maximum subsidence is normally about 80 per cent of the seam thickness. Where the worked area is stowed systematically with material imported to the working place, such as crushed rock or washery refuse, maximum subsidence is reduced to approximately 50 per cent of the seam thickness.

6 It is also observed that each observation point at the surface has both a vertical and a horizontal component of movement as illustrated in Figure 6.2. The differences in subsidence, s_1, s_2 . . . s_M, between adjacent stations, result in tilt or change in gradient of the original ground surface. Similarly, the differences in horizontal displacement d_1, d_2 . . . d_M result in change of length of the ground surface. These changes in length may be positive or negative and the ground surface is actually stretched where the subsidence is convex and shortened where it is concave. Conventionally, the measured extensions and shortenings of the ground surface are referred to as tensile and compressive strains respectively.

7 The relationship between subsidence and strain has been established empirically so that where

$$y = f(x)$$

when y is the subsidence at a point x along the profile of subsidence, measured from its point of inflection.

$$\text{Strain} = K\frac{d^2y}{dx^2}$$

in which K is a multiplier dependant upon depth as numerator and a figure in the denominator which has to be derived from local observations. Maximum values in relation to critical areas of extraction in British coalfields are as follows:

Maximum tilt: $\frac{3{\cdot}0\,Sm}{D}$

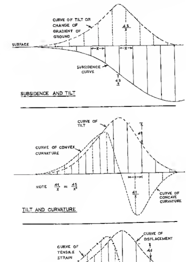
Maximum curvature: $\frac{15{\cdot}0\,Sm}{D}$

Maximum horizontal displacement: $\frac{Sm}{3}$

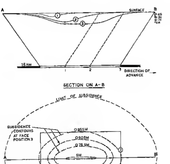
Maximum tensile strain: $\frac{Sm}{D}$

Maximum compressive strain: $\frac{2{\cdot}0\,Sm}{D}$

The patterns of tilt and displacement are basically similar as are the patterns of curvature and ground strain. They are represented in conventional form in Figure 6.3.



6.3 Conventional representation of observed ground movements.

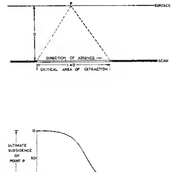


6.4 Diagrammatic illustration of dynamic subsidence development.

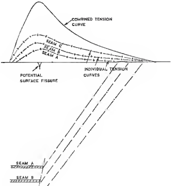
8 The description so far has been confined to a consideration of the final transverse movements across a mining area. In fact, the development of surface movement is three-dimensional, so that, in the direction of advance, subsidence develops as illustrated in Figure 6.4. The dynamic or travelling subsidence is also accompanied by horizontal strain although normally the maximum values for dynamic tilts and strains are slightly less than the maximum transverse or static values. Subsidence is also represented conventionally in plan by contours joining points of equal vertical subsidence as shown in Figure 6.4.

9 The development of surface subsidence in relation to time is shown in simple form in Figure 6.5. If a single mine working is considered in relation to a surface point P, no subsidence at the surface point will occur until the mining enters its so-called 'critical area of extraction'. The rate of subsidence development is slow as the working advances towards the surface point and accelerates rapidly after it has passed beneath and beyond it. As the working approaches the opposite perimeter of the critical area the subsidence development decelerates and amounts to 90–95 per cent of the maximum as the opposite perimeter is reached. Thereafter, there is a 5–10 per cent residual effect the duration of which is partly dependant on depth but which rarely exceeds 12 months and is very short when the working concerned is very shallow. This development curve of subsidence is remarkably consistent in British and European coalfields and the period over which subsidence occurs is therefore clearly related to:

(a) the time which a working requires to traverse the critical area of extraction;
(b) the time required for the residual 5–10 per cent to occur.


P
SURFACE
D
DIRECTION OF ADVANCE →
SEAM
1·4D
CRITICAL AREA OF EXTRACTION
ULTIMATE SUBSIDENCE OF POINT P
0
50
100%
0·7D
1·4D
2·0D
GRAPH OF SUBSIDENCE DEVLOPMENT CURVE FOR POINT P

6.5 Diagram showing development of subsidence relative to time.



6.6 Diagram illustrating accumulation of tensile ground strain and potential fissuring where several seams are worked to a common boundary.

If (a) occupies 12 months in a given set of circumstances and (b) three months, the time required for the complete subsidence of P would be 15 months. On the other hand, if mining in the same circumstances took place more rapidly, (a) might occupy only six months, and the complete subsidence of P would take place in only nine months.

The development curve remains substantially the same when the width of working is sub-critical. In general terms it can be stated that subsidence at a surface point will continue so long as mining within its critical area of extraction is taking place. Once such mining has ceased subsidence of the surface point will normally be complete within a period of one year.

10 When several seams are mined to a common boundary such as a fault there is inevitably an accumulation of surface ground movement as illustrated in Figure 6.6. Accumulations of tensile ground strain (or indeed heavy tensile ground strain from the extraction of a single seam) can result in the appearance of cracks or fissures at the ground surface. An example from the Cheadle Coalfield in Staffordshire is shown in Figure 6.7. These occurrences are usually associated with the existence of sandstone beds very near the surface. Either the tensile strength of the sandstones is exceeded or a natural joint plane or planes are opened up. Such fissures may extend for several hundreds of yards, may be from a few inches to several feet in width and, in so far as their depth is determinable, have been known to extend to 50 ft or more in depth. Such fissures are a common feature in the high tensile zones created by mining on the mountain slopes of the Welsh mining valleys. They are usually associated with the opening of existing main joint planes.

11 When the whole history of mining at a particular colliery is considered the cumulative pattern of subsidence which builds up over a long period of time is rarely, if ever, a uniform one. The whole of a single seam is never mined out, a pillar is left to support the shafts, certain areas of coal have to be left unmined for one reason or another, faults occur which cause more or less wide unworkable areas. The pattern of ultimate subsidence reflects this irregular pattern of mining so that the ultimate subsided surface is characterised by a series of subsidence depressions separated by humps or saddles. The latter represent zones of high tensile ground strain.

12 Plans of the seam areas mined in the general vicinity of the tip-complex at Merthyr Vale Colliery were included with the Memorandum of Mr R.J. Piggott, dated 20th November 1966, and already submitted to the Tribunal (not published here, Ed.). Mr K. Wardell has seen the original mine plans and mining programmes for the colliery and those included in Mr R.J. Piggott's report are here verified as being substantially correct copies. The following are the brief particulars of the mining history at Merthyr Vale:

Seam	Depth of working relative to No. 7 Tip	Thickness worked	Dates of working From To
Four feet	1,660 ft	5′ 6″	Pre-1900 to 1906
Six feet	1,680 "	5′ 0″	1907 to 1916
Nine feet	1,810 "	10′ 0″	1901 to 1913
Yard	1,840 "	3′ 0″	1916 to 1923
Seven feet	1,920 "	5′ 6″	1937 to 1945
Five feet/Gellideg	1,960 "	5′ 6″	1945 to 1961

13 Calculations of subsidence in the vicinity of the tip-complex have been made separately for each seam in contour form. These calculations

are based on critical area dimensions of 1·4D and on subsidence factors of 0·90 for caving, 0·80 for strip packing and 0·50 for stowing. Strain calculations have been based on deducing the curvature of the subsided ground surface and applying a value of $\frac{D}{15}$ for the multiplier K. All the factors used are based on other subsidence observations in the South Wales Coalfield since none had been made at Merthyr Vale. None of the general observations in South Wales have suggested any material departures from the principles of subsidence as already outlined.

14 We have directed our attention to the ground movement situation at three specific dates as follows:

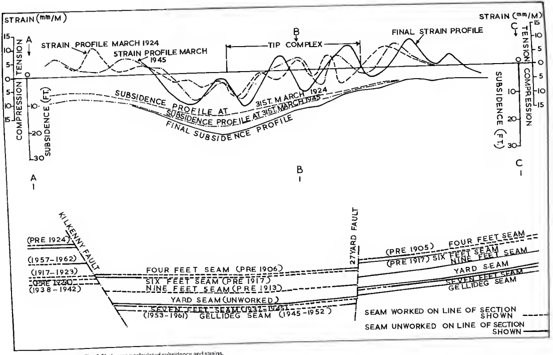
(a) October–November 1944 in relation to the failure of Tip No. 4.
(b) In September 1963 in relation to the events on Tip No. 7 at that time.
(c) In October 1966 in relation to the disaster.

15 In October–November 1944, the Seven Feet Seam was being mined directly beneath Tip No. 4, and the detailed calculations showing the ground movements at that time are shown in Figure 6.8 (in wallet). At the time of failure the maximum change in gradient of the ground surface was approximately 1 in 200 under the centre of the tip and the maximum calculated tensile ground strain was 1 to 2 mm/metre or 0·1–0·2 per cent. We cannot discount the possibility that the tensile ground strain could, at that time, have been concentrated at some existing joint plane and that a locally more intensive movement may have occurred. In our view it is at least a possibility that these ground movements could have contributed to that failure.

16 The last workings to take place within influencing distance of Tip No. 7 were in the Gellideg Seam in February 1961. We are completely satisfied that no mining subsidence or ground strain therefrom was actually being caused in the vicinity of Tip No. 7 either in September 1963 or in October 1966. We take the view therefore that movement from current mine workings could not have contributed to the occurrences at Tip No. 7 in September 1963 nor, indeed, to the disaster of October 1966.

17 The total composite picture of subsidence and strain at the time of the disaster is depicted in Figure 6.9 (in wallet). We emphasise that, to the extent that this is a summation of separate calculations for the individual seams worked between the opening of the colliery and 1966, it is broadly qualitative rather than specifically quantitative. The subsidence is irregular with a saddle, as it were, running north-west, south-east, the northern end of which lies immediately under Tip No. 7. This saddle is characterised by calculated high cumulative tensile ground strains. To the east and beneath Tips 1, 2 and 3 is a zone of compression and another compression zone extends under Tips 4 and 5. The direction of the calculated cumulative tensile strains under Tip No. 7 is approximately south-west to north-east, i.e. perpendicular to the direction of the main joint planes of the Brithdir Beds. To the north and west of the tip-complex there is a broad zone of relatively slight tensile strain.

18 The saddle of subsidence and its associated high potential tensile strain is largely a reflection of the barren ground caused in every seam by the Twenty-Seven Yard Fault. This situation has existed and developed throughout the period of mining as is indicated in the cross-section shown on Figure 6.10. A small proportion of this accumulation of tension took place prior to 1926 but was accentuated by the Seven Feet and Gellideg Seam workings between 1937 and 1961.



6.10 Section A-B-C (see Fig. 6.9) showing calculated subsidence and strains.

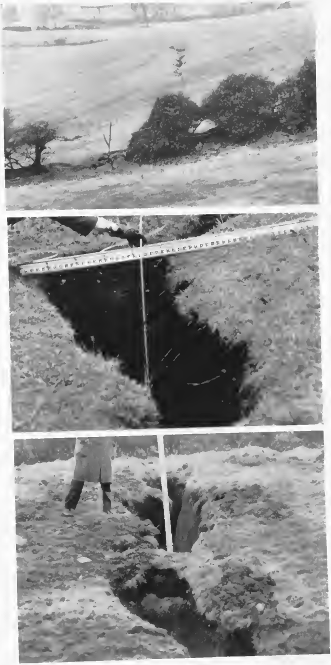
19 The high tensile zone to the south and west of the tip-complex is similarly associated with the barren ground of the Kilkenny Fault. Fissures in the Brithdir Beds above the Brithdir Seam are clearly visible and some details of these are shown in the photographs associated with Figure 6.11. These fissures also parallel the main joint planes in the Brithdir Beds. We are of the opinion that similar fissures have probably been opened out in the sandstones immediately beneath Tip No. 7, by the high tensile strains apparently concentrated there by the development of mining subsidence. Such fissures would probably be associated with the main joint planes of the Brithdir Beds. It is impossible to verify this conclusion visually because the area concerned is partly overtipped and partly overlain by boulder clay and head.

20 It is a characteristic effect of tension from mine subsidence on rocks near the ground surface, particularly when these are not of great thickness, that fractures or fissures open up which reflect the horizontal displacement of the ground rather than the calculated tensile ground strain. That is to say, if the tensile strain is of sufficient intensity to fracture the rock bed or to open up a joint plane or planes in it, the width of the fracture or fractures is usually much greater than one would anticipate from a consideration of the tensile strain alone. While it is possible, largely by analogy, to predict that fissures will occur, and to indicate their general direction, it is not possible to predict how many fissures will be caused, nor how wide they may be, nor their lateral extent.

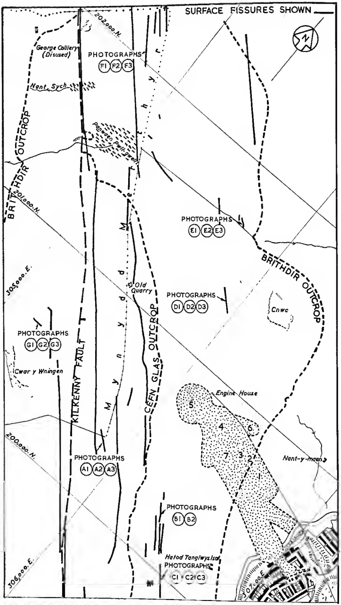
21 It seems to us that ground water from the general catchment area to the north and west would move along the aquifers created by the main and subsidiary joint planes of the Brithdir Beds above the Brithdir Seam towards the tip-complex. There it would tend to be funnelled towards the opened joint planes within the high tensile zone. With restricted outlet to the east because of compression under Tips 1, 2 and 3 and with limited run off due to decreasing tension and even some compression to the south it seems possible, in our view, that there could have been an accumulation of water in the opened joints beneath Tip No. 7, which might, particularly after substantial rainfall, develop a considerable pressure head. We believe that this situation created by the ground movements from mining could have been a major reason for the considerable outflow of water. We feel that the circumstances described in this report, together with our own broad conclusions about them, should be taken into account in considering the hydrogeology in the region of the tip-complex.

22 Although the geological plans and sections indicated that the Brithdir Seam was present as a single seam, boreholes made since the disaster reveal that the seam has apparently split into two leaves separated by some 8 to 10 yd of seatearth and shale. Moreover, there are indications that both leaves were mined to some extent in the nineteenth century and certainly prior to the sinking of Merthyr Vale Colliery. Plan No. H.12 of Mr Piggott's report to the Tribunal showed the recorded workings in the Brithdir Seam which are now believed to represent workings in the lower leaf.

23 Both leaves were apparently no more than 17 in. in thickness and must therefore have been mined in conjunction with some fireclay and possibly ironstone. Plan No. H.12 indicates a form of pillar mining which would be the most practicable system at the time. Subsidence from such workings differs both in mechanism and in extent from that caused by longwall mining as practised exclusively at the Merthyr Vale Colliery. We are of the view that the pillars left as indicated on Plan H.12, and particularly in the vicinity of the tip-complex, would be substantial enough to bear indefinitely the pressures imposed on them by the weight of overlying strata. Also, we believe that the overlying

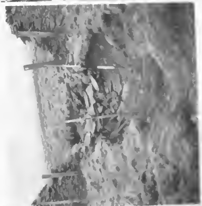


6.7 Surface fissures at Cheadle Coalfield.



6.11 Aberfan. Plan showing surface fissures and location of photographs.

A1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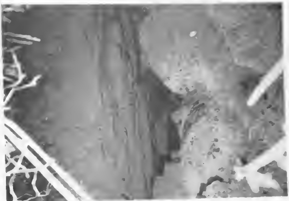
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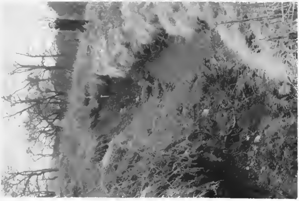
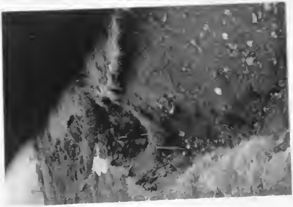
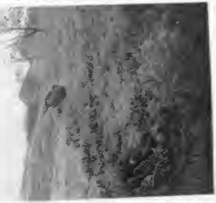


B1

B2



C1



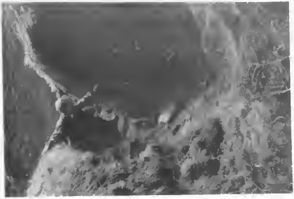
C2

C3

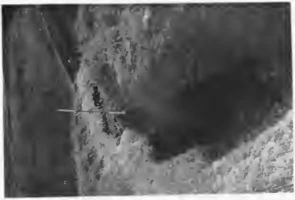
D1

D2

D3



E3



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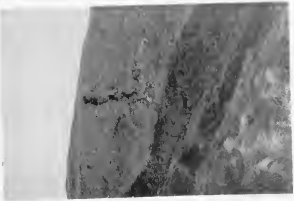
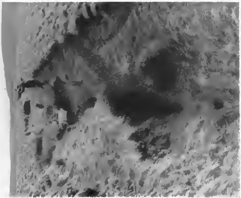
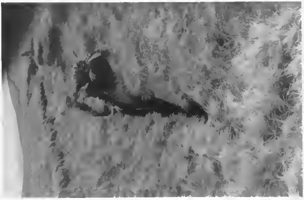


E1



F1



F2

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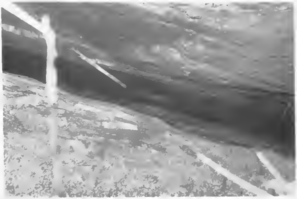
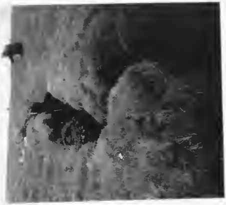


G3

G2



G1

Brithdir Sandstones would be sufficiently thick and strong to bridge over the apparently narrow mine openings.

24 We are therefore reasonably satisfied (although we recognise somewhat less certainty than in the case of the Merthyr Vale subsidence) that neither subsidence nor failure of the Brithdir old mine workings caused ground movement in the vicinity of Tip No. 7.

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Meteorological conditions relating to the Aberfan Inquiry

A. BLEASDALE BA BSc[1]

1 In relation to Aberfan the three nearest rainfall stations are at Mountain Ash, Treharris and Merthyr Tydfil. All three stations are within 5 miles of Aberfan and the nearest at Darranlas Reservoir, Mountain Ash, is within 1¾ miles, approximately south-west of the tip. The rainfall records of these three stations all go back more than 50 years, for Mountain Ash to 1899. There is little fault to be found with the data for this station throughout 68 years.

2 On 2nd February 1967 I inspected all three stations. They had last been inspected by the Meteorological Office rainfall station inspector in February 1963 when certain improvements had been suggested to the authorities responsible. In the case of Mountain Ash these were very slight. I found that the improvements had been carried out.

3 I formed the opinion that Mountain Ash is by far the most suitable rainfall station for estimating rainfall in the neighbourhood of Aberfan for a number of reasons:

- 3.1 Proximity and a somewhat similar right-bank situation in the adjacent valley to the west.
- 3.2 The siting of the gauge is good and rather better than at the other two stations.
- 3.3 The achievement of 68 years of trustworthy data can be matched by only a small proportion of rainfall stations throughout the United Kingdom. A long record is particularly useful for the analysis of rainfall averages and frequencies, in order to appreciate any rainfall event in correct perspective.

4 I have examined maps of the distribution of rainfall over South Wales both for long-period average rainfall and for a number of individual months and days including October 1966 and 3rd December 1960. There is a recurrent pattern of rainfall distribution, caused by the presence of high ground reaching to well over 1500 ft within distances of 5 to 10 miles to the west of Mountain Ash, such that reinfall often decreases slightly from west to east in this area. This suggests that rainfall at Derrenlas Reservoir may usually be a little higher, perhaps by 2 or 3 per cent, than at the site of the tip at Aberfan. On the other hand, slightly higher rainfall on the high ground above the tip will compensate this difference. I have therefore reached the conclusion thet for the rainfall in the general neighbourhood of the Aberfan tip the data for Mountain Ash may be taken as they stand, using the data for Treharris and Merthyr Tydfil as supporting evidence with regard to rainfall sequences, bearing in mind the lower average rainfall at these two more distant stations. The use of three neighbouring stations in this way is a great help in detecting any errors or omissions in the data. In the overwhelming majority of years the Mountain Ash data have been accepted as faultless. Occasional errors, detected in only a few years, have been trivial.

[1] Principal Scientific Officer in the Meteorological Office.

5 Mountain Ash is again by far the most suitable rainfall station in relation to the event at Abercwmboi in December 1960, for which I have been asked to supply rainfall data. The site of the Abercwmboi outburst is less than a mile from Darranlas Reservoir to the west, and according to my estimate from the map it is roughly 350 ft higher at about 900 ft above mean sea level. Higher ground in the immediate neighbourhood reaches to more than 1300 ft and the Mountain Ash rainfall data must underestimate, though possibly only slightly, rainfall over the high ground, in particular for the fall preceding the Abercwmboi outburst.

6 I have been asked to supply rainfall data relevant to two other events at sites other than Aberfan, in December 1939 at Abercynon, and in March 1965 at Tymawr. The site of the former event is midway between the rainfall stations at Treharris and Llanwood Reservoir, Pontypridd, and it is appropriate to use the mean values derived from the rainfall data for the two stations. The site of the latter is less than 1 mile from Llanwood Reservoir and the data for this station by itself are quite suitable. Though I have not personally inspected the rainfall station at Llanwood Reservoir, it was also inspected in February 1963, and I have satisfied myself with regard to the quality of the data.

7 In reverse chronological order, the full list of dates and places concerning events for which I have been asked to examine rainfall data covering the preceding periods is:

21.10.66	Aberfan
29.3.65	Tymawr
Aug. to Nov. 1963	Aberfan
4.12.60	Abercwmboi
21.11.44	Aberfan
5.12.39	Abercynon

8 Rainfall data can be analysed and summarised in a great variety of ways according to the manner in which the information is to be applied. Where long-period storage is involved, either in reservoirs or as groundwater in permeable geological strata, cumulative totals over several years may be relevant, and certainly totals over many months are required. For river-flow and stream-flow, cumulative totals over periods of days are of interest, though emphasis may be on falls for a few hours only in considering the period of high flow from small drainage areas. In so far as soil-moisture conditions have an influence on stream-flow, rainfall and evaporation for a preceding period of one month or several months may be relevant according to circumstances. For any application in which very rapid run-off is involved, rainfall over a few hours or even minutes, with consideration of rainfall intensities as well as cumulative amounts, is of great importance.

9 For the analysis and discussion of rainfall totals over the longer periods (one month upwards) Meteorological Office practice is to adopt a standard period for comparison purposes. This standard period, in current usage 1916 to 1950, is studied in considerable detail, and rainfall amounts for months, seasons or years are often expressed as percentages of the averages which have been calculated for the standard period. The discussion of 'wet' years and 'dry' years, or other periods, invariably implies comparison with averages for the standard period in use.

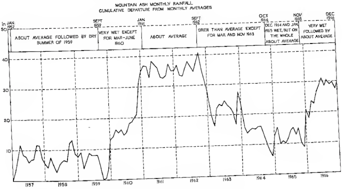
10 For the analysis and discussion of rainfall over shorter periods than one month interest in comparisons with average conditions decreases, and interest becomes centred more and more, as the period decreases, on the maximum falls which have ever been recorded, and on the frequency distribution of near-maximum amounts. The average rainfall in a day over the whole of Britain is only a fraction of an inch, and over

the greater part of the country only a small fraction. It is of little interest to compare with this average the daily values of well over 1 in. which occur, and it is far more meaningful to examine them in relation to their frequencies.

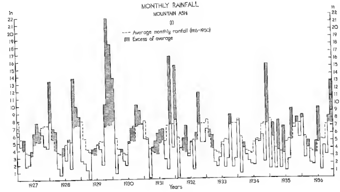
11 All the relevant rainfall data have been examined with these lines of thought in mind, in an effort to discover the most significant rainfall facts in connection with each event. Among the rainfall analysis summaries prepared in convenient form for discussion are:

- 11.1 Tabular and graphical presentation of monthly rainfall totals for more than 12 months up to each of the dates mentioned.
- 11.2 Tabular and graphical presentation of daily rainfall amounts for more than one month up to each of the dates.
- 11.3 Tabular presentation of cumulative totals of rainfall for various periods of consecutive days, ranging from 1 to 30, immediately preceding each of the dates.
- 11.4 A statement on the observed frequencies of occurrence for the largest of the consecutive day totals preceding each date. For any occasion and any number of consecutive days the statement gives the actual frequency with which the amount has been reached or exceeded in the same number of consecutive days, from an analysis of the data covering more then 60 years.
- 11.5 Graphical presentation of the deviations from average of monthly rainfall in the Aberfan neighbourhood, in one form covering 40 years, and in other forms covering 10 years, 1957 to 1966, with references to individual days of outstandingly heavy falls of rain.
- 11.6 A summary of outstanding events in South Wales rainfall history over about 100 years, which includes 3rd December 1960 as one of the very notable dates.

12 The conclusions which emerge most clearly from a study of the rainfall data alone are summarised for each of the dates below. It is not out of the question that additional or more precise conclusions could be drawn from continued study, especially if the rainfall data can be closely linked with other important factors known to have a bearing on any of the events.



7.1 Mountain Ash monthly rainfall Cumulative departure from monthly averages


MONTHLY RAINFALL
MOUNTAIN ASH
(1)
--- Average monthly rainfall (1916-1950)
▨ Excess of average
in
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
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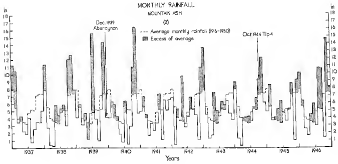
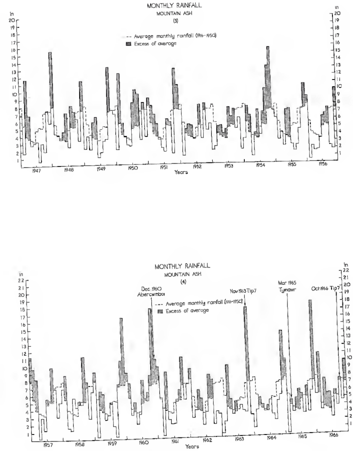
2
1
1927
1928
1929
1930
1931
1932
1933
1934
1935
1936
Years


MONTHLY RAINFALL
MOUNTAIN ASH
(2)
Dec. 1939 Abercynon
--- Average monthly rainfall (1916-1950)
▨ Excess of average
Oct 1944 Tip 4
in
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
Years



7.2 Monthly rainfall Mountain Ash 1927-66.

13 **Aberfan, 21.10.66** (rainfall station Mountain Ash)

The rainfall of October 1966 in the neighbourhood of Aberfan, though heavy, was by no means unusual for this area (see Figure 7.2). The total for the month, 7·71 in., was only 8 per cent higher than the average for October, 7·15 in. Also this followed a September with less than 75 per cent of average rainfall, including a period of 14 days in the second half of that month, 16th to 29th, with no rain at all (see Table 1). February and April 1966 were very wet in relation to their rainfall averages, but it is necessary to go back to December 1965 to find a strikingly wet month. The total was then 19·14 in. or 262 per cent of the December average.

In the three-week period immediately preceding 21st October the heaviest rainfall was on the 19th, with substantial amounts also on the 17th and 18th, but very little on the 20th. The falls for one day, two days together or three days together for the 17th to 19th were not very remarkable, and gave amounts corresponding to a frequency of roughly twice a year. (Where the frequency of a fall is mentioned this is derived from the number of times on which the amount measured has been reached or exceeded during the same number of consecutive days, or in a later context hours.) The cumulative total which gave the nearest approach to a frequency classification of 'unusual' was that for two consecutive days, 18th to 19th, with 2·75 in. This corresponds to an average frequency of 17 times in 10 years, not far short of twice a year. Cumulative totals for periods longer than three days failed to reach the twice a year amounts.

There was a period of three or four weeks up to 19th December 1965 during which there was roughly twice as much rain for any selected number of consecutive days. The corresponding frequencies of occurrence were mostly of the order of once in eight years.

For rainfall intensities during very short periods reckoned in hours or minutes it is necessary to go distances of 6 or 7 miles to the north of Aberfan for the nearest recording rain-gauges (Llwynon, Pontsticill and Tredegar). The charts from these gauges have been examined. There is no evidence of any very intense short-period rainfall. Intensities failed to exceed those which, on the average, occur at least once a year almost anywhere in the United Kingdom. (The most intense fall at Tredegar was 0·73 in. during 9 hours from about midnight on the 18th to 09.00 on the 19th, which included 0·45 in. in 1½ hours beginning at about 06.15. From the daily totals of 1·89 in. at Mountain Ash and 1·56 in. at Tredegar, it appears that the Aberfan neighbourhood may have experienced intensities about 20 per cent higher, say 0·88 in. in 9 hours, including 0·54 in. in 1½ hours. The falls expected with an average frequency of once a year at any station in the United Kingdom are 0·93 in. in 9 hours and 0·53 in. in 1½ hours.)

In terms of rainfall intensities, daily rainfall amounts, cumulative rainfall over several days, or individual monthly totals, the rainfall data appear to indicate that October 1966 and the period of several months before that were not very remarkable. December 1965 was, however, very wet and during the last few years there have been a number of similarly wet months, of which November 1963 and December 1964 with January 1965 taken together were specially notable. It may therefore be of interest to examine the general sequence of rainfall for several years in terms of winter half-years, October to March, when evaporation is almost negligible, and summer half-years, April to September, when, on the average, evaporation accounts for about 80 per cent of the rainfall in this area. Though there were some individual wet months, both winter and summer half-years were drier than average during the period October 1962 to September 1964 (see Table 2). In particular summer half-year rainfall was not much greater than evaporation. There had been a very wet period of 18 months followed by an approximately average period of 18 months before that. From October 1964 both winter half-years and summer half-years have been progressively

Table 1

Daily rainfall in inches

	Mountain Ash		Lanwood Reservoir		Mountain Ash							
Year	1966		1965		1963				1960		1944	
Date	Sept.	Oct	Feb	Mar	Aug	Sept	Oct	Nov	Nov	Dec	Oct	Nov
1		·47		·09	0	·12	22	14	1 04	·34		0
2		·57		0	·08	01	20	36	69	·48		0
3		19		18	09	·04	38	·30	1 17	5 42		·02
4		·28		0	tr	·38	02	1 06	·06	08		16
5		·04		0	0	09	12	69	0			69
6		21		0	0	·05	·14	01	04			·92
7		13		0	·04	25	03	·51	0			·05
8		0		0	0	·40	·23	21	0			31
9		04		0	·42	·04	tr	75	1 21			·03
10		·24		0	·10	·02	0	56	1 35		20	·15
11		0		0	·02	0	0	1·71	·32		1 46	·10
12		·32		·16	·03	0	tr	16	28		18	·13
13		·06		10	08	0	0	·19	1·04		1·47	·14
14		1·01		03	0	0	·10	20	·62		·15	03
15		·01		·74	46	0	55	·64	51		·42	0
16	0	·14		0	61	0	08	·02	55		·65	1 62
17	0	·49		28	01	01	02	3·10	52		1·34	47
18	0	86		0	tr	tr	tr	2·15	65		92	1 95
19	0	1·89		25	·06	0	·46	58	89		1 42	1·60
20	0	·07		·41	10	0	tr	·21	36		·84	04
21	0	0	0	·09	09	0	14	1·01	35		0	72
22	0		0	·58	tr	0	05	15	·28		07	
23	0		0	·17	48	tr	·02	20	·46		·02	
24	0		0	·27	·07	1·08	tr	62	41		0	
25	0		0	·72	60	·70	0	1 46	2·03		0	
26	0		0	0	·17	·15	0	06	·74		·07	
27	0		0	0	·03	0	0	tr	·02		01	
28	0		0	0	0	·10	·01	42	17		·18	
29	0			0	0	09	24	0	·56		0	
30	·15				33	0	·19	·10	1·40		0	
31					37		·10				0	

wetter, with summer half-year rainfall appreciably greater than evaporation, especially in 1966. It is therefore possible that in those circumstances in which *cumulative* rainfall can make itself effective over a period of several years, the situation in October 1966 may have shown a greater positive departure from the average than at any time since the autumn of 1962 and possibly earlier into 1961. Graphs of cumulative departure of monthly rainfall from average support this suggestion, but also indicate that the cumulative wetness leading to autumn 1966 was by no means so marked as in the wet period of 18 months centred on mid-1960 (see Figure 7.1).

This method of treating rainfall data by cumulative departure from average may have some relevance to the consideration of fluctuations of ground-water levels.

Table 2
Generalised rainfall characteristics of winter and summer half-years

Winter (Oct-March)	Summer (April–September)	
1959–60 1960–61	1960	Very wet
1961–62	1961 1962	About average
1962–63 1963–64	1963 1964	Drier than average
1964–65 1965–66	1965 1966	Progressively wetter

Division of the year into winter and summer half-years is convenient for linking rainfall with evaporation. In the winter half-year evaporation is almost negligible. In the summer half-year evaporation on the average accounts for about 80 per cent of the rainfall in this area. Fluctuations of rainfall from month to month, smoothed over in the above generalisations, are shown in detail by monthly rainfall graphs.

14 **Tymawr, 29.3.65** (rainfall station Pontypridd)

The rainfall immediately preceding this event was totally unremarkable (see Figure 7.2). March was marginally drier than average in this area with 0·72 in. on the 25th, 0·58 in. on the 22nd and 0·74 in. on the 15th. Only one other fall, 0·41 in. on the 20th, exceeded one-third of an inch. February was unusually dry with measurable rain or snow on only two days and a total for the month of only 0·07 in. December 1964 and January 1965 were together very wet (145 per cent of the combined average) and so also, going back in time, were November and March 1963. But on the whole, even including these few wet months, conditions were drier than average for about 2½ years back to October 1962, and not far from average for another 18 months before that.

15 **Aberfan, August to November 1963** (rainfall station Mountain Ash)

My information is that it has not been possible to fix the date of the event at Aberfan in 1963, though it has been suggested that it could not have been later than 8th November. There was no rainfall sequence in 1963 comparable with that leading up to 21st October 1966 until the sequence leading up to 12th November. March was very wet, April and June were rather wetter than average, but the summer half-year as a whole was slightly drier than average, with rainfall little greater than evaporation, followed by October rainfall of less than 50 per cent of average. Generalising to smooth fluctuations in individual months, drier than average conditions preceded by about average conditions extended back to early 1961.

Although November itself was very wet, with 17·50 in. or 238 per cent of the November average, three-fifths of the month's total fell in the second half of the month. The most notable rainfall sequence of the year was that including the 17th with 3·10 in. and the 18th with 2·15 in., well beyond the possible dates of interest.

The sequence leading up to 12th November gave consecutive-day totals corresponding to frequencies of two to three times a year, that is rather smaller amounts than the equivalent totals preceding 21st October 1966. The sequence later in the month, including the 17th to 18th, was much more remarkable, some of the consecutive-day totals corresponding to frequencies of only once in about 10 years.

16 **Abercwmboi, 4.12.60** (rainfall station Mountain Ash)

The rainfall sequence leading up to this event was in some respects, for this area, in a class by itself. For the whole of South Wales the rainfall of 3rd December 1960 certainly ranks as one of the six outstanding daily events in a rainfall history now going back about 100 years. Considering the total area covered by very heavy falls and the total volume of water precipitated, it may rank as high as second or third. For the Mountain Ash area in particular the fall of the 3rd, 5·42 in., is especially notable since it followed almost immediately on a very wet November (17·72 in. or 241 per cent of average) with nearly another inch on 1st to 2nd December combined. The only equivalent daily fall in nearly 70 years at Mountain Ash, 5 46 in. on 3rd November 1931, followed a period of 24 days with slightly less than 1 in. as the total fall, and rainfall very much below average throughout September and October. The period October 1929 to January 1930 produced a very high four-month total (more than 60 in.) and some very high consecutive-day totals, though without a daily fall reaching 4 in. There were some other notable sequences in 1936, 1940 and 1946, but again without any falls exceeding 4 in.

The Abercwmboi event also came towards the end of the notably wet period of about 18 months beginning in October 1959, after the drier than average summer of that year, and approximately average conditions on the whole for some years before that.

The daily fall of 5 42 in. on 3rd December and the 20 consecutive-day total ending on that day rank as once in 33 or 34 years occurrences for this area. Other consecutive-day totals of intermediate duration rank as once in 11 years to once in 22 years occurrences since they have been more or less matched in a number of other years some of which are mentioned above.

The frequency classification shows that the rainfall sequence leading up to the Abercwmboi event was quite different from the sequences leading up to each of the other five dates, including 21st October 1966, which are being discussed. In quantitative terms, for any period of consecutive days from 1 to 30, and probably more, the rainfall amount preceding the Abercwmboi event was roughly twice to three times as large as the greatest amount in the same number of consecutive days preceding 21st October 1966.

17 **Aberfan, 21.11.44** (rainfall station Mountain Ash)

The sequence of daily rainfall immediately before this event provides a fairly close parallel to that preceding 21st October 1966, except that nearly all consecutive-day totals from 1 to 30 were appreciably larger. This is reflected in the frequency classification, for which the two- or three-day values prove most striking at about once in two years, as against nearly twice a year for the October 1966 equivalents. The falls of November 1944 can hardly be classed as unusual at this frequency level though they were more so than those of October 1966.

A parallel which may be significant is that, in November 1944 as in October 1966, between the heavy rainfall sequence (culminating in two consecutive days of heaviest rainfall) and the subsequent event, there was a day of almost negligible rainfall, 0·04 in. on 20th November 1944, and 0·07 in. on 20th October 1966, the event being in each case on the 21st. For November 1944 this has been confirmed by a reference to a 'fine night' on 20th–21st November, which is all the more apt since the 'rainfall day' labelled 20th November in fact means, following the usual convention, the period of 24 hours *ending* at 09.00 GMT on the 21st.

Before November 1944 monthly rainfall totals fluctuated over a fairly narrow range about the average, and it is necessary to go back nearly two years to January 1943 for a very wet month, which with December 1942 formed a two-month wet period. Before that May 1942 was the only very wet month in another two-year period December 1940 to November 1942 which on the whole was about average. The very wet two months October to November 1940 which preceded this are rather remote from the event under discussion. There is little or no tendency towards increasing wetness in the few years preceding November 1944, a point of some difference in the comparison with October 1966, though possibly not a very important one.

18 **Abercynon, 5.12.39** (rain fall stations Treharris and Pontypridd; mean values for the two stations considered)

The daily rainfall sequence preceding this event was peculiar compared with all five others which have been discussed, in that the heaviest rainfall occurred more than a week before the event. Looking at the rainfall data (see Table 3) one would have thought that if rainfall had been a *direct* major contributory cause of the occurrence, this would have happened earlier, at latest on the 27th or 28th November following 3·56 in. for the 25th and 26th combined. Since for 21st October 1966 and 21st November 1944 there seems to have been a delay of one day or rather more during which the rainfall (if rainfall was in fact a cause) was making itself effective, the suggestion from the rainfall data alone in December 1939 seems to be that there must have been a much longer delaying mechanism at work, extending over several days.

The largest daily fall (25th November, 2·57 in.) and the largest consecutive-day totals for this occasion, which always include 25th to 26th November some eight days before the event, correspond to frequencies of occurrence of about once in three years. They form a nearer approach to the unusual than for any other rainfall sequence discussed, except that preceding 4th December 1960. Quantitatively they range up to 70 per cent larger for the 15-day total and 100 per cent larger for the 30-day total compared with the corresponding totals for October 1966. For the largest two to three-day amounts, which may be more significant than the longer period totals, they are only 25 to 30 per cent larger than for October 1966 at Aberfan.

In 1939 November, July and January were very wet, in 1938 November, October and January, end in 1937 February and January, representing a rather greater frequency of individual wet months than in some of the periods of a few years before other events in the list. There were also some notably dry periods and the three years as a whole were not much different from average. There was, however, a steady progression, through large monthly fluctuations, from drier than average in 1937 to wetter than average in 1939. A slow cumulative rainfall effect may have been in operation.

19 The six rainfall sequences examined are very diverse, though with some parallels, perhaps closest for 1966 and 1944, and with some great dissimilarities.

Comparison of the rainfall near Aberfan before 21st October 1966 and 21st November 1944 shows some dissimilarity for the preceding few years, but a rather close parallel for the preceding few weeks, especially the build-up to the largest two-day rainfall, followed by a pause of one day before the event. This suggests a fairly direct rainfall action with only a short delay of one to two days before the heaviest rainfall became effective.

Rainfall would not appear to be important on this basis for the Tymawr event of 29th March 1965. A very prolonged delaying mechanism from the high two-month rainfall of December 1964 and January 1965, or earlier, would need to be brought in to suggest any significent rainfall action at all.

Table 3
Daily rainfall means in inches for year 1939 of Treharris and Lanwood Reservoir

Day	November	December
1	·01	39
2	·21	01
3	·06	·60
4	·30	·31
5	·90	·07
6	·23	
7	49	
8	1 00	
9	·09	
10	·03	
11	0	
12	·03	
13	·07	
14	·73	
15	39	
16	·63	
17	13	
18	95	
19	·01	
20	0	
21	0	
22	1·07	
23	1 47	
24	·01	
25	2 67	
26	99	
27	·07	
28	49	
29	59	
30	33	
31		

The rainfall information for the 1963 event at Aberfan is puzzling in the opposite sense. If a build-up to two-dey rainfall, at least comparable with that on 18th to 19th October 1966, was important on this occasion, it would point to a date later than any which has been suggested as possible.

The apparently fairly long delay period after the heaviest rainfall preceding 5th December 1939 at Abercynon, compared with 1966 and 1944 at Abarfan, is also puzzling on the basis of rainfall data alone. But on this different site it is possible that information from another field of study can be taken in conjunction with the rainfall data to resolve the matter.

The event at Abercwmboi on 4th December 1960 is not at all surprising. The precise mechanisms by which the rain-water entered the ground, to emerge later in an outburst in one place, must be very interesting, but are outside the field of rainfall study. Apart from these details the rainfall data alone are sufficient to provide the broad explanation of what happened. The rainfall sequence for more than a month, culminating in the fall of more than 5 in. on 3rd December, was quite extraordinary. The volume of water precipitated must have been enormous, as the resulting calamitous floods at Treforest and elsewhere also testify. There is no close similarity between the rainfall associated with the Abercwmboi outburst and that for any of the other five occasions dealt with.

20 Rainfall data from the rain-gauge at the Phurnacite Plant at Aberaman have been quoted, in particular in connection with the Abercwmboi event of 4th December 1960. I have inspected this rain-gauge and also compared the data with those for Darranlas Reservoir, Mountain Ash, less than 1 mile away, both for the period before 4th December 1960 and for recent years. I have carried out this comparison in conjunction with a study of maps of rainfall distribution. There is no doubt that the Phurnacite Plant values are persistently low, on the average by 15–20 per cent. Any genuine rainfall difference between this site and Darranlas Reservoir cannot possibly be more than 5 per cent, on the average, and I would doubt even that much difference, though it could be more on a few individual occasions. The major part of the deficiency is due to bad exposure, on a flat roof, of the Phurnacite Plant gauge. The readings should not be used for any serious quantitative purpose.

There is another important point. Normal practice with a daily rain-gauge is to make rainfall readings in the morning, the standard hour of observation being 0900 GMT. Each reading is then 'thrown back' to the previous day's date. This leads to the definition of the 'rainfall day' as the period of 24 hours beginning at 0900 GMT on the stated date. The Phurnacite Plant readings are not thrown back, as can be seen from the following comparison (see Table 4). They are for 24-hour periods *ending* on the stated date. This is very important for any use of the data in connection with stream-flow and response times. The Phurnacite Plant monthly totals also need slight adjustment because of the need to throw back the daily values.

Table 4

			Phurnacite Plant	Mountain Ash
1960	July		6·34	8·04
	August		4·81	5·54
	September		5·65	6·28
	October		7·75	8·57
	November		15·72	17·72
	December		8·05	10·82
	Six-month total		48·32	56·97
1960	November	30		1·40
	December	1	0·34	0·34
		2	0·31	0·48
		3	0·44	5·42
		4	{3·14}	0·08
		5		0·03
		6	0·02	

(Rainfall readings in inches)

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